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Search for the Standard Model Higgs boson decay to $\mu^+\mu^-$ with the ATLAS detector

ATLAS Collaboration^{*}



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ABSTRACT

A search is reported for Higgs boson decay to $\mu^+\mu^-$ using data with an integrated luminosity of 24.8 fb^{-1} collected with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ and 8 TeV at the CERN Large Hadron Collider. The observed dimuon invariant mass distribution is consistent with the Standard Model background-only hypothesis in the 120–150 GeV search range. For a Higgs boson with a mass of 125.5 GeV, the observed (expected) upper limit at the 95% confidence level is 7.0 (7.2) times the Standard Model expectation. This corresponds to an upper limit on the branching ratio $\text{BR}(H \rightarrow \mu^+\mu^-)$ of 1.5×10^{-3} .

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1. Introduction

The Standard Model (SM) describes a wide range of particle physics phenomena to a high degree of precision. In the SM, the Brout–Englert–Higgs (BEH) mechanism [1–3] spontaneously breaks the electroweak (EW) gauge symmetry and generates masses for the W and Z gauge bosons as well as for the charged fermions via Yukawa couplings [4–6]. In searches for the Higgs boson predicted by the BEH mechanism, the ATLAS and CMS Collaborations have discovered a new particle, via decays into gauge bosons [7,8], with a mass of approximately 125.5 GeV and measured properties consistent with those predicted by the SM [9–12].

Higgs boson decays to $b\bar{b}$, $\tau^+\tau^-$ and $\mu^+\mu^-$ can be measured at the LHC with their SM branching ratios proportional to the squares of the fermion masses. The SM branching ratio for the $H \rightarrow \mu^+\mu^-$ decay is 21.9×10^{-5} for a Higgs boson mass (m_H) of 125 GeV [13,14]. The $H \rightarrow \mu^+\mu^-$ decay has a clean final state signature that allows a measurement of the Higgs boson coupling to second-generation fermions. The dominant irreducible background is the $Z/\gamma^* \rightarrow \mu^+\mu^-$ process, which has an approximately three orders of magnitude higher production rate compared to that of the expected signal.

In this Letter a search for the $H \rightarrow \mu^+\mu^-$ decay of the SM Higgs boson is presented. This search for the presence of a narrow $H \rightarrow \mu^+\mu^-$ resonance, with a signal width determined by experimental resolution, is performed by fitting the invariant mass distribution in the 110–160 GeV region. This range allows determining background shape and normalisation and setting a limit

on the dimuon decay of the SM Higgs boson with a mass of 125.5 GeV. Section 2 gives a description of the experimental setup and summarises the data sample and Monte Carlo (MC) simulation samples used to model the signal process and to develop an analytical model for the background processes. Sections 3 and 4 describe the event selections and categorisation. Analytical models used to describe invariant mass distributions for signal and background processes are discussed in Section 5, and systematic uncertainties are detailed in Section 6. The results are presented in Section 7.

2. Experimental setup, data and simulated samples

This search is performed on the data sample recorded in 2011 and 2012 by the ATLAS detector in pp collisions at the LHC at $\sqrt{s} = 7$ and 8 TeV, respectively. ATLAS [15] is a general-purpose particle detector with a cylindrical geometry and consists of several subdetectors surrounding the interaction point and covering almost the full solid angle.¹ The trajectories and momenta of charged particles are measured within the pseudorapidity range of $|\eta| < 2.5$ by multi-layer silicon pixel and microstrip detectors as well as a transition radiation tracker. The tracking system is immersed in a 2 T magnetic field produced by a superconducting solenoid, and is surrounded by a high-granularity

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

^{*} E-mail address: atlas.publications@cern.ch.

liquid-argon (LAr) electromagnetic sampling calorimeter covering $|\eta| < 3.2$. An iron and scintillator tile hadronic calorimeter provides coverage in the range $|\eta| < 1.7$. The LAr calorimeters also provide measurements of electromagnetic and hadronic energy deposits in the region $1.5 < |\eta| < 4.9$. The muon spectrometer surrounds the calorimeters and consists of three large air-core superconducting magnets with a toroidal field of 0.5 T in the barrel region and 1 T in the forward regions, and a system of precision tracking chambers; it provides coverage for $|\eta| < 2.7$. The muon spectrometer also includes fast detectors for triggering covering $|\eta| < 2.4$.

Events were recorded with a trigger [16] requiring at least one muon candidate with transverse momentum $p_T > 18$ GeV for 7 TeV data and $p_T > 24$ GeV for 8 TeV data. This trigger is approximately 70% efficient for muons with $|\eta| < 1.05$ and approximately 90% efficient for muons with $|\eta| > 1.05$. The differences in the efficiency are mostly due to the different geometrical acceptance of the muon trigger system in these regions. For 8 TeV data, events were also recorded with a dimuon trigger requiring at least two muon candidates with transverse momenta of $p_T > 18$ GeV and $p_T > 8$ GeV. After applying data quality requirements, the total integrated luminosity of the selected data sample is $4.5 \pm 0.1 \text{ fb}^{-1}$ for 7 TeV data and $20.3 \pm 0.6 \text{ fb}^{-1}$ for 8 TeV data. The associated systematic uncertainties are summarised in Section 6.

At the LHC, SM Higgs boson production is dominated by the gluon fusion (ggF) process with the next two most important contributions arising from the vector boson fusion (VBF) process and production in association with vector bosons (VH). The signal MC samples are generated in 5 GeV steps of the Higgs boson mass from 120 GeV to 150 GeV. The ggF and VBF samples are generated at next-to-leading-order (NLO) in QCD with POWHEG [17,18] with the parton showering modelled by PYTHIA8 [19] for the 8 TeV samples and PYTHIA [20] for the 7 TeV samples. The CT10 [21] parton distribution functions (PDFs) are used in POWHEG, with the ATLAS Underlying Event Tune, AU2 [22]. The ggF Higgs boson p_T spectrum in POWHEG is tuned to agree with the prediction from HRES [23,24]; this procedure shifts the Higgs boson p_T spectrum to slightly smaller values. The VH samples are generated with PYTHIA8, using AU2 and the CTEQ6 [25] PDFs.

The predicted SM Higgs boson cross-sections and branching ratios are compiled in Refs. [13,14,26]. The cross section for the ggF process is calculated at next-to-next-to-leading-order (NNLO) [27–32] in QCD and NLO electroweak (EW) corrections are applied [33,34], assuming that the QCD and EW corrections factorise. The cross section for the VBF process is calculated with full NLO QCD and EW corrections [35–37] and approximate NNLO QCD corrections [38]. The cross section for the VH process is calculated at NNLO [39,40] in QCD, and NLO EW radiative corrections [41] are applied. The branching ratios for $H \rightarrow \mu^+ \mu^-$ decays as a function of m_H are calculated using HDECAY [42].

The following MC event generators are used to simulate background processes: ALPGEN [43] + HERWIG [44] for W + jets, MC@NLO [45] + HERWIG for $t\bar{t}$, tW and $t\bar{b}$, ACERMC [46] + PYTHIA for $tq\bar{b}$, POWHEG + PYTHIA8 for Z/γ^* and $q\bar{q} \rightarrow WW$, gg2WW [47] + HERWIG for $gg \rightarrow WW$, POWHEG [48] + PYTHIA for WZ and ZZ and MADGRAPH [49,50] + PYTHIA for $W\gamma^*$. WW , WZ , ZZ and $W\gamma^*$ production are referred to as diboson production later in the text. In addition, contributions from W boson production in association with one or more jets (W + jets), where one of the jets is misidentified as a muon, are estimated using a data control region containing same-sign dimuon events as described in Ref. [9].

The signal and background MC samples are processed through the ATLAS detector simulation [51] based on GEANT4 [52], followed by the same reconstruction algorithms that are used for collision data. The effects arising from multiple collisions in the same or neighbouring bunch crossings (pile-up) are included in the MC

simulation, matching the pile-up conditions of the selected data sample.

3. Event selection

Events are required to contain at least one reconstructed pp collision vertex candidate with at least three associated tracks each with $p_T > 0.4$ GeV. The vertex with the largest sum of p_T^2 of tracks is considered to be the primary vertex. Muon candidates [53] are reconstructed by matching tracks in the inner detector to tracks reconstructed in the muon spectrometer. In addition to stringent track quality requirements imposed for muon identification, the muon tracks must be consistent with having originated from the primary vertex. All selected muon candidates are required to be within $|\eta| < 2.5$. Muon candidates must pass track and calorimeter isolation requirements that scale with the p_T of the muon track. The isolation is calculated as the scalar sum of the p_T of additional tracks or the E_T of calorimeter energy deposits within cone of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the muon track, normalised by p_T^μ . For 8 TeV data, each muon with $p_T^\mu > 20$ (15) GeV is required to have a normalised track isolation smaller than 0.12 (0.08) and a normalised calorimetric isolation less than 0.30 (0.18). For 7 TeV data, equivalent values for $p_T^\mu > 15$ GeV are 0.15 and 0.2 for track and calorimetric isolation, respectively. Due to different pile-up conditions, different isolation criteria are used for 7 TeV and 8 TeV data.

Jets are reconstructed from clusters of calorimeter cells using the anti- k_t algorithm [54,55] with a radius parameter of 0.4. The selected jets must satisfy $E_T > 25$ GeV for $|\eta| < 2.4$ and $E_T > 30$ GeV for $2.4 \leq |\eta| < 4.5$. Muon candidates overlapping with the selected jets within a cone of radius $\Delta R = 0.4$ are removed from the analysis. In the pseudorapidity range $|\eta| < 2.5$, jets originating from b -quarks are identified using a b -tagging algorithm [56,57] with an efficiency of approximately 80%, determined from $t\bar{t}$ MC events, and with a misidentification rate for selecting light-quark or gluon jets of less than 1%. The missing transverse momentum [58], E_T^{miss} , is the magnitude of the vector sum of the p_T of muons, electrons, photons, jets and clusters of calorimeter cells with $|\eta| < 4.9$ not associated with these objects.

Corrections are applied to simulated MC samples in order to account for differences between data and MC simulation for the trigger and identification efficiency and for the muon momentum scale and resolution. The trigger and reconstruction efficiency corrections are measured using $Z \rightarrow \mu^+ \mu^-$ events and are found to be within 2% of unity. The muon momentum corrections are determined by comparing the reconstructed invariant mass distribution of $Z \rightarrow \mu^+ \mu^-$ events in data with that from simulated events; these corrections are within 0.1% of unity.

$H \rightarrow \mu^+ \mu^-$ candidate events are selected by requiring exactly two oppositely charged muons with transverse momentum $p_T^{\mu_1} > 25$ GeV and $p_T^{\mu_2} > 15$ GeV for the leading and subleading muon, respectively. Selected events must contain at least one muon identified by the trigger system within a cone of radius $\Delta R = 0.15$ centred on the reconstructed muon candidate. The dominant background in this search is $Z/\gamma^* \rightarrow \mu^+ \mu^-$ production, followed by smaller backgrounds from single and pair production of top quarks and diboson processes. To suppress backgrounds from top quark pair production and diboson processes, events are required to have $E_T^{\text{miss}} < 80$ GeV. The dimuon invariant mass distribution $m_{\mu^+ \mu^-}$ and the dimuon transverse momentum $p_T^{\mu^+ \mu^-}$ for data and MC events passing all the selection requirements so far are shown in Fig. 1. The number of expected signal events for $m_H = 125$ GeV, the expected background contributions, and the number of observed data events in the $m_{\mu^+ \mu^-}$ region from 122.5 to 127.5 GeV

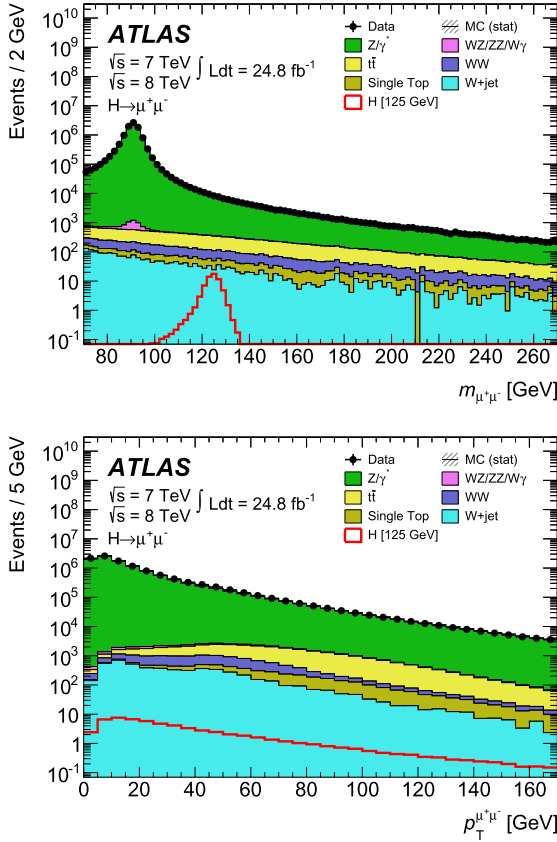


Fig. 1. The distribution of the dimuon invariant mass (top) and dimuon momentum (bottom) for 7 TeV and 8 TeV data with all the selection requirements described in Section 3. The expected signal is shown for $m_H = 125$ GeV.

are shown in Table 1. The MC background yields are given to illustrate the expected background composition. The selection efficiency times acceptance for signal events with $m_H = 125$ GeV after all selection criteria described thus far is approximately 55%.

The expected background processes produce smooth $m_{\mu^+\mu^-}$ distributions in the search window, allowing the total background normalisation and shape in each category to be derived from fitting the data as described in Section 5. The $m_{\mu^+\mu^-}$ distribution is examined in the range 110–160 GeV. This range is larger than the 120–150 GeV search window in order to account for signal resolution effects and to allow sufficient sidebands for background normalisation.

4. Event categorisation

To increase sensitivity to the Higgs boson signal, the selected events are separated into seven mutually exclusive categories with different signal-to-background ratios based on their muon pseudorapidity (η_μ), $p_T^{\mu^+\mu^-}$, and VBF dijet signature. Events produced in the VBF process are characterised by two forward jets with little hadronic activity between them. The VBF category is thus defined by requiring the events to have at least two jets with an invariant mass greater than 500 GeV, $|\eta_{\text{jet}_1} - \eta_{\text{jet}_2}| > 3$ and $\eta_{\text{jet}_1} \times \eta_{\text{jet}_2} < 0$. In events with more than two jets, those with the highest p_T are used in the selection. Events with at least one jet identified as originating from a b -quark are excluded from the VBF category.

The events that are not selected for the VBF category are classified using $p_T^{\mu^+\mu^-}$. Signal events have on average larger values of $p_T^{\mu^+\mu^-}$ than the Z/γ^* background events. Therefore, the remaining

Table 1

Number of expected signal events for $m_H = 125$ GeV, number of expected background events predicted by the MC simulation, and number of observed data events within a window of $|m_H - m_{\mu^+\mu^-}| \leq 2.5$ GeV after all selection criteria are applied. Only statistical uncertainties are given. The theoretical systematic uncertainty on the dominant Z/γ^* background is about 4%. The MC background yields are given to illustrate the expected background composition.

| | 7 TeV | 8 TeV |
|-------------------|----------------|-----------------|
| Signal (125 GeV) | 5.6 ± 0.1 | 32.7 ± 0.2 |
| Z/γ^* | 3110 ± 40 | 16660 ± 270 |
| $WZ/ZZ/W\gamma$ | 2.2 ± 0.2 | 12.3 ± 0.7 |
| $t\bar{t}$ | 75.6 ± 1.8 | 509.2 ± 2.7 |
| WW | 23.2 ± 0.5 | 123.3 ± 1.6 |
| Single top | 7.2 ± 0.9 | 54.5 ± 0.6 |
| $W + \text{jets}$ | 3.2 ± 1.5 | 38 ± 4 |
| Total Bkg. | 3220 ± 40 | 17390 ± 270 |
| Observed | 3344 | 17745 |

Table 2

Expected signal yields (N_S) for $m_H = 125$ GeV and the ratio $N_S/\sqrt{N_B}$ using the simulated MC background yields (N_B) within a window of $|m_H - m_{\mu^+\mu^-}| \leq 2.5$ GeV for each of the event categories under study. In addition, the full width at half maximum (FWHM) of the signal $m_{\mu^+\mu^-}$ distribution, modelled as described in Section 5, is given. Also shown are χ^2/ndof of the standalone fits to the $m_{\mu^+\mu^-}$ distribution in each category using models described in Section 5. The 7 TeV VBF category does not include a sufficient number of events to compute a meaningful χ^2 value. The goodness of fit for the background description in this category was verified using MC simulation to ensure that the background model provides a consistent description of the 7 TeV and 8 TeV VBF categories.

| \sqrt{s} [TeV] | Category | N_S | $\frac{N_S}{\sqrt{N_B}}$ | FWHM [GeV] | χ^2/ndof |
|---------------------|------------------------------------|-------|--------------------------|---------------|----------------------|
| 8 | non-cen. low $p_T^{\mu^+\mu^-}$ | 6.1 | 0.07 | 6.6 | 49.8/48 |
| 8 | cen. low $p_T^{\mu^+\mu^-}$ | 2.6 | 0.06 | 5.5 | 52.8/48 |
| 8 | non-cen. medium $p_T^{\mu^+\mu^-}$ | 10.4 | 0.15 | 6.6 | 45.1/48 |
| 8 | cen. medium $p_T^{\mu^+\mu^-}$ | 4.7 | 0.13 | 5.6 | 36.7/48 |
| 8 | non-cen. high $p_T^{\mu^+\mu^-}$ | 5.5 | 0.13 | 7.2 | 26.7/48 |
| 8 | cen. high $p_T^{\mu^+\mu^-}$ | 2.6 | 0.10 | 6.0 | 32.3/48 |
| 8 | VBF | 0.8 | 0.09 | 7.0 | 18.6/19 |
| 7 | non-cen. low $p_T^{\mu^+\mu^-}$ | 1.0 | 0.03 | 6.8 | 42.0/48 |
| 7 | cen. low $p_T^{\mu^+\mu^-}$ | 0.5 | 0.03 | 5.3 | 43.5/48 |
| 7 | non-cen. medium $p_T^{\mu^+\mu^-}$ | 1.8 | 0.06 | 6.9 | 41.2/48 |
| 7 | cen. medium $p_T^{\mu^+\mu^-}$ | 0.8 | 0.05 | 5.5 | 34.4/48 |
| 7 | non-cen. high $p_T^{\mu^+\mu^-}$ | 0.9 | 0.05 | 7.5 | 60.0/48 |
| 7 | cen. high $p_T^{\mu^+\mu^-}$ | 0.5 | 0.05 | 5.9 | 56.2/48 |

events are separated into three $p_T^{\mu^+\mu^-}$ categories: low (< 15 GeV), medium (15–50 GeV) and high (> 50 GeV). To further improve the search sensitivity, each of these three categories is also subdivided into a central category with $|\eta_{\mu_1}| < 1$ and $|\eta_{\mu_2}| < 1$ and a non-central category containing all remaining events. This value for the η_μ boundary has been chosen by scanning a range of η_μ values and selecting a value with the highest signal sensitivity. The muon momentum measurement for the central muons is more precise, producing a narrower $m_{\mu^+\mu^-}$ distribution for signal events in the central category and thus resulting in a higher overall signal sensitivity. Table 2 shows the signal event yields, $N_S/\sqrt{N_B}$ ratios, approximate signal width and results of the fits to the data, described in Section 5, for all analysis categories.

5. Signal and background models

Analytical models are used to describe the $m_{\mu^+\mu^-}$ distributions for signal and background processes. The simulated samples detailed in Section 2 are used to develop background models

which are designed to describe essential features of the background $m_{\mu^+\mu^-}$ distributions, dominated by Z/γ^* , while having sufficient flexibility to describe different categories and to absorb potential differences between data and MC simulation.

The background model selected to describe the $m_{\mu^+\mu^-}$ distribution for the $p_T^{\mu^+\mu^-}$ categories is the sum of a Breit–Wigner (BW) function convoluted with a Gaussian function (GS), and an exponential function divided by x^3 :

$$P_B(x) = f \cdot [\text{BW}(M_{\text{BW}}, \Gamma_{\text{BW}}) * \text{GS}(\sigma_{\text{GS}}^B)](x) + (1 - f) \cdot C \cdot e^{A \cdot x} / x^3, \quad (1)$$

where x represents $m_{\mu^+\mu^-}$ and f represents the fraction of the BW component when each individual component is normalised to unity. C is an overall normalisation coefficient. The σ_{GS}^B parameters in each category are fixed to the average $m_{\mu^+\mu^-}$ resolution in that category as determined from the MC simulation of Z/γ^* . The background model for the VBF category is the product of a Breit–Wigner and an exponential function:

$$P_B(x) = \text{BW}(M_{\text{BW}}, \Gamma_{\text{BW}}, x) \cdot e^{A \cdot x}. \quad (2)$$

For all categories, the BW parameters are fixed to $M_{\text{BW}} = 91.2$ GeV and $\Gamma_{\text{BW}} = 2.49$ GeV. The parameters f , A and the overall background normalisation are determined from fits to the data, as shown in Fig. 2 for the central medium $p_T^{\mu^+\mu^-}$ category. Similar fit quality is observed for all other categories.

The signal model is obtained from simulated Higgs boson signal samples, where contributions from the ggF, VBF and VH Higgs boson production processes are added together. This model is the sum of a Crystal Ball (CB)² and a Gaussian function:

$$P_S(x) = f_{\text{CB}} \cdot \text{CB}(x, m, \sigma_{\text{CB}}, \alpha, n) + (1 - f_{\text{CB}}) \cdot \text{GS}(x, m, \sigma_{\text{GS}}^S), \quad (3)$$

where x represents $m_{\mu^+\mu^-}$ and f_{CB} represents the fraction of the CB contribution when each individual component is normalised to unity. The parameters α and n define the power-law tail of the CB distribution. The parameters σ_{CB} and σ_{GS}^S denote the widths of the CB and GS distributions, respectively. The parameters m , σ_{CB} and σ_{GS}^S are determined from the fits to the simulated Higgs boson samples. In order to improve stability of the fits, the remaining parameters f_{CB} , α and n are fixed to values determined from empirical tests where a range of possible values have been tested. Fig. 3 shows how the signal model reproduces the simulation for the medium $p_T^{\mu^+\mu^-}$ category for the expected signal dimuon mass distributions. Similar fit quality is obtained for all other categories. The signal model parameters are linearly interpolated in steps of 1 GeV between the generated signal samples.

To derive the results presented in Section 7, a binned maximum likelihood fit to the observed $m_{\mu^+\mu^-}$ distributions in the range 110–160 GeV is performed using the sum of the signal and background model. The fit is done simultaneously in all seven categories with separate distributions for 7 TeV and 8 TeV data. Free fit parameters include the background model fit parameters described earlier and an overall background normalisation in each category. The signal model parameters are fixed in the fit to data except for the $H \rightarrow \mu^+\mu^-$ signal strength μ_S defined such that $\mu_S = 0$ corresponds to the background-only hypothesis and $\mu_S = 1$ corresponds to the SM $H \rightarrow \mu^+\mu^-$ signal hypothesis.

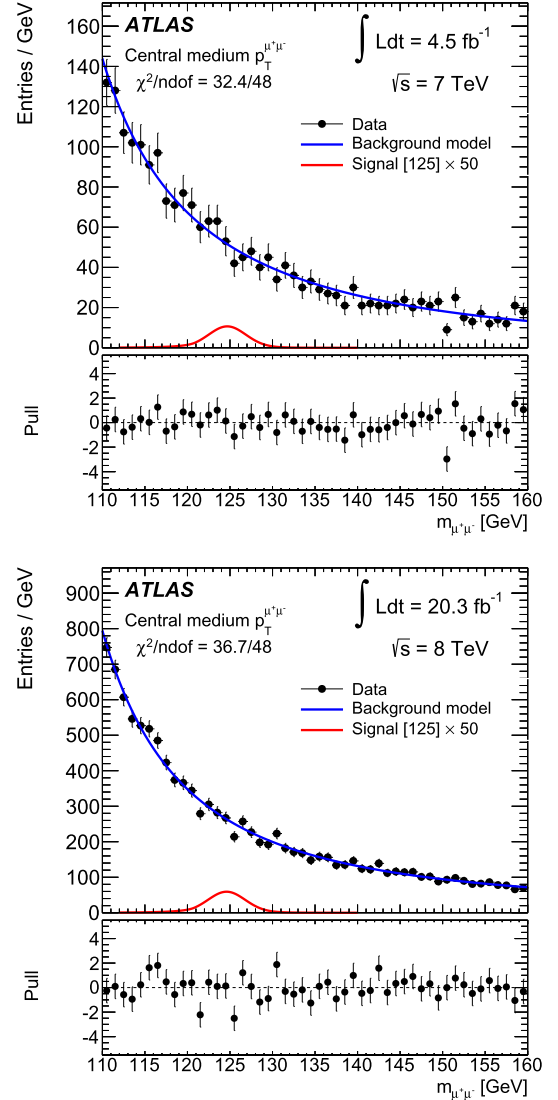


Fig. 2. The background model fits to the $m_{\mu^+\mu^-}$ distribution for the central medium $p_T^{\mu^+\mu^-}$ category for 7 TeV (top) and 8 TeV (bottom) data. The statistical uncertainties are given for the data points. The expected signal is shown for $m_H = 125$ GeV and is scaled by a factor of 50.

Table 3

Main sources of experimental and theoretical uncertainty on the signal yield, excepting the error from mismodelling bias. “QCD scale” indicates the theoretical uncertainty on the Higgs boson production due to missing higher-order corrections estimated by varying the QCD renormalisation and factorisation scales, while “PDFs + α_s ” indicates uncertainty due to parton distribution functions, as described in Refs. [13,14]. The ranges for the uncertainties cover the variations among different categories and data-taking periods.

| Source (experimental) | Uncertainty (%) |
|-----------------------------|--------------------------------------|
| Luminosity | ± 1.8 (7 TeV), ± 2.8 (8 TeV) |
| Muon efficiency | ± 1 |
| Muon momentum res. | ± 1 |
| Muon trigger | ± 1.5 |
| Muon isolation | ± 1.1 |
| Pile-up reweighting | ± 1 |
| Jet energy scale | $+3.4$ -4.5 (VBF) |
| Source (theory) | Uncertainty (%) |
| Higgs boson branching ratio | ± 7 |
| QCD scale | ± 8 (ggF), ± 1 (VBF, VH) |
| PDFs + α_s | ± 8 (ggF), ± 4 (VBF, VH) |
| ggF uncert. in VBF | ± 22 |
| Multi-parton inter. in VBF | ± 9 (ggF), ± 4 (VBF) |

² A Gaussian function with a power-law tail.

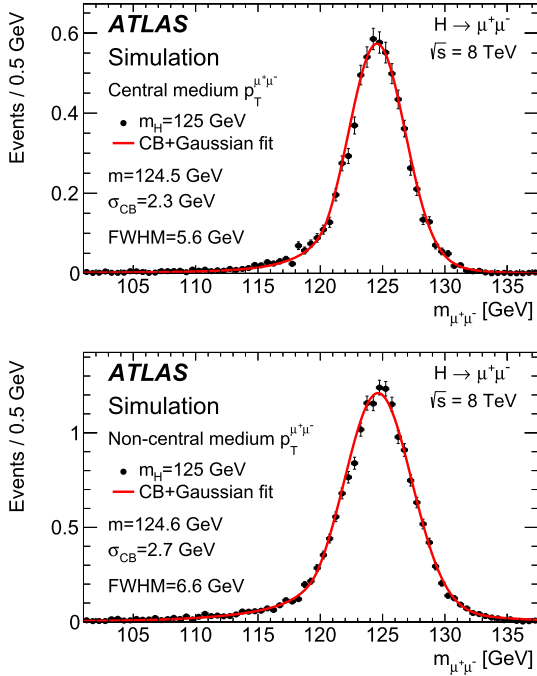


Fig. 3. The signal model fit to the $m_{\mu^+\mu^-}$ distribution for the central (top) and non-central (bottom) simulated Higgs boson events for $m_H = 125$ GeV in the medium $p_T^{\mu^+\mu^-}$ category for $\sqrt{s} = 8$ TeV.

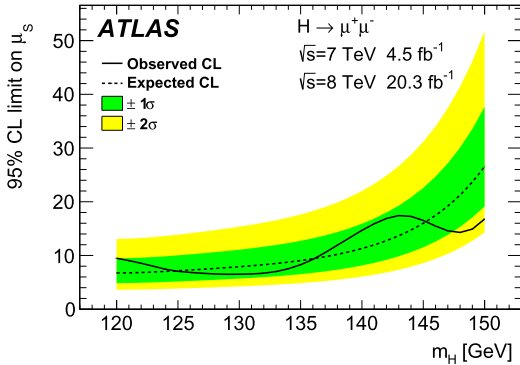


Fig. 4. Observed (solid) and expected (dashed) 95% CL upper limits on the $H \rightarrow \mu^+\mu^-$ signal strength as a function of m_H over the mass range 120–150 GeV. The dark- and light-shaded regions indicate the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands on the expected limit, respectively.

6. Systematic uncertainties

The main theoretical and experimental sources of uncertainty on the number of expected signal events are shown in Table 3. The uncertainty on the integrated luminosity is $\pm 1.8\%$ for 7 TeV data [59] and $\pm 2.8\%$ for 8 TeV data; it is obtained following the same methodology as that detailed in Ref. [59], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

Sources of experimental uncertainty include the efficiency of the muon trigger, reconstruction, identification, and isolation requirements, as well as the muon momentum scale and resolution. Uncertainties on the jet energy scale and resolution affect the selection of jets used in the VBF category definitions. Smaller uncertainties arise from pile-up and the primary vertex selection. The total experimental uncertainty on the predicted signal yield is a

Table 4

Observed and expected 95% CL upper limits on the $H \rightarrow \mu^+\mu^-$ signal strength μ_s for different values of m_H .

| m_H [GeV] | 120 | 125 | 130 | 135 | 140 | 145 | 150 |
|-------------|-----|-----|-----|-----|------|------|------|
| Obs. | 9.5 | 7.1 | 6.5 | 8.3 | 14.7 | 16.5 | 16.8 |
| Exp. | 6.7 | 7.2 | 7.9 | 9.1 | 11.3 | 16.0 | 26.6 |

sum in quadratures of the individual uncertainties. Shape variations of the signal distributions are negligible.

The theoretical uncertainties on the production and $H \rightarrow \mu^+\mu^-$ decay of a SM Higgs boson of mass $m_H = 125$ GeV are taken from Refs. [13,14]. The uncertainty on the relative populations of the $p_T^{\mu^+\mu^-}$ categories, due to the uncertainty on the description of the Higgs boson p_T spectrum arising from missing higher-order corrections, is determined by varying the QCD renormalisation, factorisation and resummation scales used in the HRES program. To evaluate these uncertainties, the scales are independently varied up and down by a factor of two while keeping their ratio between 0.5 and 2.0. The ggF contribution to the VBF category has large uncertainties due to missing higher-order corrections; they are estimated using the method described in Ref. [26]. The uncertainties associated with the modelling of multi-parton interactions (MPI) are estimated by turning off the MPI modelling in the event generation, according to the recommendations in Ref. [26].

In addition to the samples described in Section 2, samples of the dominant Z/γ^* background are generated with POWHEG + PYTHIA8 and parameterised with a detector response measured using simulated MC events. These samples contain approximately 170 times more events than expected in the data and are used to validate the background models and to derive systematic uncertainties due to potential mismodelling bias. This bias is estimated by fitting the parametrised signal plus background model to the simulated $m_{\mu^+\mu^-}$ background distribution in the mass range 110–160 GeV where the signal strength μ_s is a free parameter. The bias is then defined as the root mean square of the signal yield obtained from the fit for Higgs boson masses in the range 120–150 GeV. This uncertainty varies from 3% to 20% of the statistical uncertainty on the signal strength μ_s , depending on the selection category and data-taking period.

7. Results and conclusions

The statistical procedure used to interpret the data is summarised in Ref. [7]. The observed data is consistent with the expected backgrounds and no evidence for a signal is found. Upper limits are computed on the signal strength μ_s using a modified frequentist CL_s method [60,61] based on a Poisson log-likelihood ratio statistical test.

The observed and expected 95% confidence level (CL) limits on the $H \rightarrow \mu^+\mu^-$ signal strength are shown in Fig. 4. Table 4 summarises the observed and expected limits for different values of m_H . Including the systematic uncertainties described in Section 6 changes the expected limit by approximately 2% for $m_H = 125$ GeV.

To conclude, a search for Higgs boson decay to $\mu^+\mu^-$ in 24.8 fb $^{-1}$ of pp collisions at $\sqrt{s} = 7$ and 8 TeV at the LHC has been performed with the ATLAS experiment. The observed data is consistent with the expected backgrounds. No evidence for a signal is observed and upper limits are set on the signal strength as a function of the Higgs boson mass. For a SM Higgs boson with a mass of 125.5 GeV, the observed (expected) limit on the signal strength μ_s at the 95% CL is 7.0 (7.2) times the SM prediction. Assuming a Higgs boson mass of 125.5 GeV and the SM production cross

section, which is allowed to vary within its uncertainty, the 95% CL upper limit on the $H \rightarrow \mu^+ \mu^-$ branching ratio is 1.5×10^{-3} .

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Boonekamp¹³⁷, A. Borisov¹²⁹, G. Borissov⁷¹, M. Borri⁸³, S. Borroni⁴², J. Bortfeldt⁹⁹, V. Bortolotto^{135a,135b}, K. Bos¹⁰⁶, D. Boscherini^{20a}, M. Bosman¹², H. Boterenbrood¹⁰⁶, J. Boudreau¹²⁴, J. Bouffard², E.V. Bouhova-Thacker⁷¹, D. Boumediene³⁴, C. Bourdarios¹¹⁶, N. Bousson¹¹³, S. Boutouil^{136d}, A. Boveia³¹, J. Boyd³⁰, I.R. Boyko⁶⁴, J. Bracinik¹⁸, A. Brandt⁸, G. Brandt¹⁵, O. Brandt^{58a}, U. Bratzler¹⁵⁷, B. Brau⁸⁵, J.E. Brau¹¹⁵, H.M. Braun^{176,*}, S.F. Brazzale^{165a,165c}, B. Brelrier¹⁵⁹, K. Brendlinger¹²¹, A.J. Brennan⁸⁷, R. Brenner¹⁶⁷, S. Bressler¹⁷³, K. Bristow^{146c}, T.M. Bristow⁴⁶, D. Britton⁵³, F.M. Brochu²⁸, I. Brock²¹, R. Brock⁸⁹, C. Bromberg⁸⁹, J. Bronner¹⁰⁰, G. Brooijmans³⁵, T. Brooks⁷⁶, W.K. Brooks^{32b}, J. Brosamer¹⁵, E. Brost¹¹⁵, J. Brown⁵⁵, P.A. Bruckman de Renstrom³⁹, D. Bruncko^{145b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{20a}, G. Bruni^{20a}, M. Bruschi^{20a}, L. Bryngemark⁸⁰, T. Buanes¹⁴, Q. Buat¹⁴³, F. Bucci⁴⁹, P. Buchholz¹⁴², R.M. Buckingham¹¹⁹, A.G. Buckley⁵³, S.I. Buda^{26a}, I.A. Budagov⁶⁴, F. Buehrer⁴⁸, L. Bugge¹¹⁸, M.K. Bugge¹¹⁸, O. Bulekov⁹⁷, A.C. Bundock⁷³, H. Burckhart³⁰, S. Burdin⁷³, B. Burghgrave¹⁰⁷, S. Burke¹³⁰, I. Burmeister⁴³, E. Busato³⁴, D. Büscher⁴⁸, V. Büscher⁸², P. Bussey⁵³, C.P. Buszello¹⁶⁷, B. Butler⁵⁷, J.M. Butler²², A.I. Butt³, C.M. Buttar⁵³, J.M. Butterworth⁷⁷, P. Butti¹⁰⁶, W. Buttinger²⁸, A. Buzatu⁵³, M. Byszewski¹⁰, S. Cabrera Urbán¹⁶⁸, D. Caforio^{20a,20b}, O. Cakir^{4a}, P. Calafiura¹⁵, A. Calandri¹³⁷, G. Calderini⁷⁹, P. Calfayan⁹⁹, R. Calkins¹⁰⁷, L.P. Caloba^{24a}, D. Calvet³⁴, S. Calvet³⁴, R. Camacho Toro⁴⁹, S. Camarda⁴², D. Cameron¹¹⁸, L.M. Caminada¹⁵, R. Caminal Armadans¹², S. Campana³⁰, M. Campanelli⁷⁷, A. Campoverde¹⁴⁹, V. Canale^{103a,103b}, A. Canepa^{160a}, M. Cano Bret⁷⁵, J. Cantero⁸¹, R. Cantrill^{125a}, T. Cao⁴⁰, M.D.M. Capeans Garrido³⁰, I. Caprini^{26a}, M. Caprini^{26a}, M. Capua^{37a,37b}, R. Caputo⁸², R. Cardarelli^{134a}, T. Carli³⁰, G. Carlino^{103a}, L. Carminati^{90a,90b}, S. Caron¹⁰⁵, E. Carquin^{32a}, G.D. Carrillo-Montoya^{146c}, J.R. Carter²⁸, J. Carvalho^{125a,125c}, D. Casadei⁷⁷, M.P. Casado¹², M. Casolino¹², E. Castaneda-Miranda^{146b}, A. Castelli¹⁰⁶, V. Castillo Gimenez¹⁶⁸, N.F. Castro^{125a}, P. Catastini⁵⁷, A. Catinaccio³⁰, J.R. Catmore¹¹⁸, A. Cattai³⁰, G. Cattani^{134a,134b}, S. Caughron⁸⁹, V. Cavaliere¹⁶⁶, D. Cavalli^{90a}, M. Cavalli-Sforza¹², V. Cavasinni^{123a,123b}, F. Ceradini^{135a,135b}, B. Cerio⁴⁵, K. Cerny¹²⁸, A.S. Cerqueira^{24b}, A. Cerri¹⁵⁰, L. Cerrito⁷⁵, F. Cerutti¹⁵, M. Cerv³⁰, A. Cervelli¹⁷, S.A. Cetin^{19b}, A. Chafaq^{136a}, D. Chakraborty¹⁰⁷, I. Chalupkova¹²⁸, P. Chang¹⁶⁶, B. Chapleau⁸⁶, J.D. Chapman²⁸, D. Charfeddine¹¹⁶, D.G. Charlton¹⁸, C.C. Chau¹⁵⁹, C.A. Chavez Barajas¹⁵⁰, S. Cheatham⁸⁶, A. Chegwidden⁸⁹, S. Chekanov⁶, S.V. Chekulaev^{160a}, G.A. Chelkov^{64,f}, M.A. Chelstowska⁸⁸, C. Chen⁶³, H. Chen²⁵, K. Chen¹⁴⁹, L. Chen^{33d,g}, S. Chen^{33c}, X. Chen^{146c}, Y. Chen⁶⁶, Y. Chen³⁵, H.C. Cheng⁸⁸, Y. Cheng³¹, A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{136e}, V. Chernyatin^{25,*}, E. Cheu⁷, L. Chevalier¹³⁷, V. Chiarella⁴⁷, G. Chieffari^{103a,103b}, J.T. Childers⁶, A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁸, R.T. Chislett⁷⁷, A. Chitan^{26a}, M.V. Chizhov⁶⁴, S. Chouridou⁹, B.K.B. Chow⁹⁹, D. Chromek-Burckhart³⁰, M.L. Chu¹⁵², J. Chudoba¹²⁶, J.J. Chwastowski³⁹, L. Chytka¹¹⁴, G. Ciapetti^{133a,133b}, A.K. Ciftci^{4a}, R. Ciftci^{4a}, D. Cinca⁵³, V. Cindro⁷⁴, A. Ciochio¹⁵, P. Cirkovic^{13b}, Z.H. Citron¹⁷³, M. Citterio^{90a}, M. Ciubancan^{26a}, A. Clark⁴⁹, P.J. Clark⁴⁶, R.N. Clarke¹⁵, W. Cleland¹²⁴, J.C. Clemens⁸⁴, C. Clement^{147a,147b}, Y. Coadou⁸⁴, M. Cobal^{165a,165c}, A. Coccaro¹³⁹, J. Cochran⁶³, L. Coffey²³, J.G. Cogan¹⁴⁴, J. Coggeshall¹⁶⁶, B. Cole³⁵, S. Cole¹⁰⁷, A.P. Colijn¹⁰⁶, J. Collot⁵⁵, T. Colombo^{58c}, G. Colon⁸⁵, G. Compostella¹⁰⁰, P. Conde Muiño^{125a,125b}, E. Coniavitis⁴⁸, M.C. Conidi¹², S.H. Connell^{146b}, I.A. Connolly⁷⁶, S.M. Consonni^{90a,90b}, V. Consorti⁴⁸, S. Constantinescu^{26a}, C. Conta^{120a,120b}, G. Conti⁵⁷, F. Conventi^{103a,h}, M. Cooke¹⁵, B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁹, N.J. Cooper-Smith⁷⁶, K. Copic¹⁵, T. Cornelissen¹⁷⁶, M. Corradi^{20a}, F. Corriveau^{86,i}, A. Corso-Radu¹⁶⁴, A. Cortes-Gonzalez¹², G. Cortiana¹⁰⁰, G. Costa^{90a}, M.J. Costa¹⁶⁸, D. Costanzo¹⁴⁰, D. Côté⁸, G. Cottin²⁸, G. Cowan⁷⁶, B.E. Cox⁸³, K. Cranmer¹⁰⁹, G. Cree²⁹,

S. Crépé-Renaudin⁵⁵, F. Crescioli⁷⁹, W.A. Cribbs^{147a,147b}, M. Crispin Ortuzar¹¹⁹, M. Cristinziani²¹, V. Croft¹⁰⁵, G. Crosetti^{37a,37b}, C.-M. Cuciuc^{26a}, T. Cuhadar Donszelmann¹⁴⁰, J. Cummings¹⁷⁷, M. Curatolo⁴⁷, C. Cuthbert¹⁵¹, H. Czirr¹⁴², P. Czodrowski³, Z. Czyzula¹⁷⁷, S. D'Auria⁵³, M. D'Onofrio⁷³, M.J. Da Cunha Sargedas De Sousa^{125a,125b}, C. Da Via⁸³, W. Dabrowski^{38a}, A. Dainca¹¹⁹, T. Dai⁸⁸, O. Dale¹⁴, F. Dallaire⁹⁴, C. Dallapiccola⁸⁵, M. Dam³⁶, A.C. Daniells¹⁸, M. Dano Hoffmann¹³⁷, V. Dao⁴⁸, G. Darbo^{50a}, S. Darmora⁸, J.A. Dassoulas⁴², A. Dattagupta⁶⁰, W. Davey²¹, C. David¹⁷⁰, T. Davidek¹²⁸, E. Davies^{119,c}, M. Davies¹⁵⁴, O. Davignon⁷⁹, A.R. Davison⁷⁷, P. Davison⁷⁷, Y. Davygora^{58a}, E. Dawe¹⁴³, I. Dawson¹⁴⁰, R.K. Daya-Ishmukhametova⁸⁵, K. De⁸, R. de Asmundis^{103a}, S. De Castro^{20a,20b}, S. De Cecco⁷⁹, N. De Groot¹⁰⁵, P. de Jong¹⁰⁶, H. De la Torre⁸¹, F. De Lorenzi⁶³, L. De Nooij¹⁰⁶, D. De Pedis^{133a}, A. De Salvo^{133a}, U. De Sanctis^{165a,165b}, A. De Santo¹⁵⁰, J.B. De Vivie De Regie¹¹⁶, W.J. Dearnaley⁷¹, R. Debbe²⁵, C. Debenedetti¹³⁸, B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, I. Deigaard¹⁰⁶, J. Del Peso⁸¹, T. Del Prete^{123a,123b}, F. Deliot¹³⁷, C.M. Delitzsch⁴⁹, M. Deliyergiyev⁷⁴, A. Dell'Acqua³⁰, L. Dell'Asta²², M. Dell'Orso^{123a,123b}, M. Della Pietra^{103a,h}, D. della Volpe⁴⁹, M. Delmastro⁵, P.A. Delsart⁵⁵, C. Deluca¹⁰⁶, S. Demers¹⁷⁷, M. Demichev⁶⁴, A. Demilly⁷⁹, S.P. Denisov¹²⁹, D. Derendarz³⁹, J.E. Derkaoui^{136d}, F. Derue⁷⁹, P. Dervan⁷³, K. Desch²¹, C. Deterre⁴², P.O. Deviveiros¹⁰⁶, A. Dewhurst¹³⁰, S. Dhaliwal¹⁰⁶, A. Di Ciaccio^{134a,134b}, L. Di Ciaccio⁵, A. Di Domenico^{133a,133b}, C. Di Donato^{103a,103b}, A. Di Girolamo³⁰, B. Di Girolamo³⁰, A. Di Mattia¹⁵³, B. Di Micco^{135a,135b}, R. Di Nardo⁴⁷, A. Di Simone⁴⁸, R. Di Sipio^{20a,20b}, D. Di Valentino²⁹, F.A. Dias⁴⁶, M.A. Diaz^{32a}, E.B. Diehl⁸⁸, J. Dietrich⁴², T.A. Dietzsch^{58a}, S. Diglio⁸⁴, A. Dimitrievska^{13a}, J. Dingfelder²¹, C. Dionisi^{133a,133b}, P. Dita^{26a}, S. Dita^{26a}, F. Dittus³⁰, F. Djama⁸⁴, T. Djobava^{51b}, M.A.B. do Vale^{24c}, A. Do Valle Wemans^{125a,125g}, T.K.O. Doan⁵, D. Dobos³⁰, C. Doglioni⁴⁹, T. Doherty⁵³, T. Dohmae¹⁵⁶, J. Dolejsi¹²⁸, Z. Dolezal¹²⁸, B.A. Dolgoshein^{97,*}, M. Donadelli^{24d}, S. Donati^{123a,123b}, P. Dondero^{120a,120b}, J. Donini³⁴, J. Dopke¹³⁰, A. Doria^{103a}, M.T. Dova⁷⁰, A.T. Doyle⁵³, M. Dris¹⁰, J. Dubbert⁸⁸, S. Dube¹⁵, E. Dubreuil³⁴, E. Duchovni¹⁷³, G. Duckeck⁹⁹, O.A. Ducu^{26a}, D. Duda¹⁷⁶, A. Dudarev³⁰, F. Dudziak⁶³, L. Duflot¹¹⁶, L. Duguid⁷⁶, M. Dührssen³⁰, M. Dunford^{58a}, H. Duran Yildiz^{4a}, M. Düren⁵², A. Durglishvili^{51b}, M. Dwuznik^{38a}, M. Dyndal^{38a}, J. Ebke⁹⁹, W. Edson², N.C. Edwards⁴⁶, W. Ehrenfeld²¹, T. Eifert¹⁴⁴, G. Eigen¹⁴, K. Einsweiler¹⁵, T. Ekelof¹⁶⁷, M. El Kacimi^{136c}, M. Ellert¹⁶⁷, S. Elles⁵, F. Ellinghaus⁸², N. Ellis³⁰, J. Elmsheuser⁹⁹, M. Elsing³⁰, D. Emelianov¹³⁰, Y. Enari¹⁵⁶, O.C. Endner⁸², M. Endo¹¹⁷, R. Engelmann¹⁴⁹, J. Erdmann¹⁷⁷, A. Ereditato¹⁷, D. Eriksson^{147a}, G. Ernis¹⁷⁶, J. Ernst², M. Ernst²⁵, J. Ernwein¹³⁷, D. Errede¹⁶⁶, S. Errede¹⁶⁶, E. Ertel⁸², M. Escalier¹¹⁶, H. Esch⁴³, C. Escobar¹²⁴, B. Esposito⁴⁷, A.I. Etiennevre¹³⁷, E. Etzion¹⁵⁴, H. Evans⁶⁰, A. Ezhilov¹²², L. Fabbri^{20a,20b}, G. Facini³¹, R.M. Fakhruddinov¹²⁹, S. Falciano^{133a}, R.J. Falla⁷⁷, J. Faltova¹²⁸, Y. Fang^{33a}, M. Fanti^{90a,90b}, A. Farbin⁸, A. Farilla^{135a}, T. Farooque¹², S. Farrell¹⁵, S.M. Farrington¹⁷¹, P. Farthouat³⁰, F. Fassi^{136e}, P. Fassnacht³⁰, D. Fassouliotis⁹, A. Favareto^{50a,50b}, L. Fayard¹¹⁶, P. Federic^{145a}, O.L. Fedin^{122,j}, W. Fedorko¹⁶⁹, M. Fehling-Kaschek⁴⁸, S. Feigl³⁰, L. Feligioni⁸⁴, C. Feng^{33d}, E.J. Feng⁶, H. Feng⁸⁸, A.B. Fenyuk¹²⁹, S. Fernandez Perez³⁰, S. Ferrag⁵³, J. Ferrando⁵³, A. Ferrari¹⁶⁷, P. Ferrari¹⁰⁶, R. Ferrari^{120a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁸, D. Ferrere⁴⁹, C. Ferretti⁸⁸, A. Ferretto Parodi^{50a,50b}, M. Fiascaris³¹, F. Fiedler⁸², A. Filipčič⁷⁴, M. Filipuzzi⁴², F. Filthaut¹⁰⁵, M. Fincke-Keeler¹⁷⁰, K.D. Finelli¹⁵¹, M.C.N. Fiolhais^{125a,125c}, L. Fiorini¹⁶⁸, A. Firan⁴⁰, A. Fischer², J. Fischer¹⁷⁶, W.C. Fisher⁸⁹, E.A. Fitzgerald²³, M. Flechl⁴⁸, I. Fleck¹⁴², P. Fleischmann⁸⁸, S. Fleischmann¹⁷⁶, G.T. Fletcher¹⁴⁰, G. Fletcher⁷⁵, T. Flick¹⁷⁶, A. Floderus⁸⁰, L.R. Flores Castillo^{174,k}, A.C. Florez Bustos^{160b}, M.J. Flowerdew¹⁰⁰, A. Formica¹³⁷, A. Forti⁸³, D. Fortin^{160a}, D. Fournier¹¹⁶, H. Fox⁷¹, S. Fracchia¹², P. Francavilla⁷⁹, M. Franchini^{20a,20b}, S. Franchino³⁰, D. Francis³⁰, L. Franconi¹¹⁸, M. Franklin⁵⁷, S. Franz⁶¹, M. Fraternali^{120a,120b}, S.T. French²⁸, C. Friedrich⁴², F. Friedrich⁴⁴, D. Froidevaux³⁰, J.A. Frost²⁸, C. Fukunaga¹⁵⁷, E. Fullana Torregrosa⁸², B.G. Fulsom¹⁴⁴, J. Fuster¹⁶⁸, C. Gabaldon⁵⁵, O. Gabizon¹⁷³, A. Gabrielli^{20a,20b}, A. Gabrielli^{133a,133b}, S. Gadatsch¹⁰⁶, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea¹⁰⁵, B. Galhardo^{125a,125c}, E.J. Gallas¹¹⁹, V. Gallo¹⁷, B.J. Gallop¹³⁰, P. Gallus¹²⁷, G. Galster³⁶, K.K. Gan¹¹⁰, J. Gao^{33b,g}, Y.S. Gao^{144,e}, F.M. Garay Walls⁴⁶, F. Garberon¹⁷⁷, C. García¹⁶⁸, J.E. García Navarro¹⁶⁸, M. Garcia-Sciveres¹⁵, R.W. Gardner³¹, N. Garelli¹⁴⁴, V. Garonne³⁰, C. Gatti⁴⁷, G. Gaudio^{120a}, B. Gaur¹⁴², L. Gauthier⁹⁴, P. Gauzzi^{133a,133b}, I.L. Gavrilenko⁹⁵, C. Gay¹⁶⁹, G. Gaycken²¹, E.N. Gazis¹⁰, P. Ge^{33d}, Z. Gecse¹⁶⁹, C.N.P. Gee¹³⁰, D.A.A. Geerts¹⁰⁶, Ch. Geich-Gimbel²¹, K. Gellerstedt^{147a,147b}, C. Gemme^{50a}, A. Gemmell⁵³, M.H. Genest⁵⁵,

S. Gentile ^{133a,133b}, M. George ⁵⁴, S. George ⁷⁶, D. Gerbaudo ¹⁶⁴, A. Gershon ¹⁵⁴, H. Ghazlane ^{136b}, N. Ghodbane ³⁴, B. Giacobbe ^{20a}, S. Giagu ^{133a,133b}, V. Giangiobbe ¹², P. Giannetti ^{123a,123b}, F. Gianotti ³⁰, B. Gibbard ²⁵, S.M. Gibson ⁷⁶, M. Gilchriese ¹⁵, T.P.S. Gillam ²⁸, D. Gillberg ³⁰, G. Gilles ³⁴, D.M. Gingrich ^{3,d}, N. Giokaris ⁹, M.P. Giordani ^{165a,165c}, R. Giordano ^{103a,103b}, F.M. Giorgi ^{20a}, F.M. Giorgi ¹⁶, P.F. Giraud ¹³⁷, D. Giugni ^{90a}, C. Giuliani ⁴⁸, M. Giulini ^{58b}, B.K. Gjelsten ¹¹⁸, S. Gkaitatzis ¹⁵⁵, I. Gkialas ^{155,l}, L.K. Gladilin ⁹⁸, C. Glasman ⁸¹, J. Glatzer ³⁰, P.C.F. Glaysheer ⁴⁶, A. Glazov ⁴², G.L. Glonti ⁶⁴, M. Goblirsch-Kolb ¹⁰⁰, J.R. Goddard ⁷⁵, J. Godfrey ¹⁴³, J. Godlewski ³⁰, C. Goeringer ⁸², S. Goldfarb ⁸⁸, T. Golling ¹⁷⁷, D. Golubkov ¹²⁹, A. Gomes ^{125a,125b,125d}, L.S. Gomez Fajardo ⁴², R. Gonçalves ^{125a}, J. Goncalves Pinto Firmino Da Costa ¹³⁷, L. Gonella ²¹, S. González de la Hoz ¹⁶⁸, G. Gonzalez Parra ¹², S. Gonzalez-Sevilla ⁴⁹, L. Goossens ³⁰, P.A. Gorbounov ⁹⁶, H.A. Gordon ²⁵, I. Gorelov ¹⁰⁴, B. Gorini ³⁰, E. Gorini ^{72a,72b}, A. Gorišek ⁷⁴, E. Gornicki ³⁹, A.T. Goshaw ⁶, C. Gössling ⁴³, M.I. Gostkin ⁶⁴, M. Gouighri ^{136a}, D. Goujdami ^{136c}, M.P. Goulette ⁴⁹, A.G. Goussiou ¹³⁹, C. Goy ⁵, S. Gozpinar ²³, H.M.X. Grabas ¹³⁷, L. Graber ⁵⁴, I. Grabowska-Bold ^{38a}, P. Grafström ^{20a,20b}, K.-J. Grahn ⁴², J. Gramling ⁴⁹, E. Gramstad ¹¹⁸, S. Grancagnolo ¹⁶, V. Grassi ¹⁴⁹, V. Gratchev ¹²², H.M. Gray ³⁰, E. Graziani ^{135a}, O.G. Grebenyuk ¹²², Z.D. Greenwood ^{78,m}, K. Gregersen ⁷⁷, I.M. Gregor ⁴², P. Grenier ¹⁴⁴, J. Griffiths ⁸, A.A. Grillo ¹³⁸, K. Grimm ⁷¹, S. Grinstein ^{12,n}, Ph. Gris ³⁴, Y.V. Grishkevich ⁹⁸, J.-F. Grivaz ¹¹⁶, J.P. Grohs ⁴⁴, A. Grohsjean ⁴², E. Gross ¹⁷³, J. Grosse-Knetter ⁵⁴, G.C. Grossi ^{134a,134b}, J. Groth-Jensen ¹⁷³, Z.J. Grout ¹⁵⁰, L. Guan ^{33b}, F. Guescini ⁴⁹, D. Guest ¹⁷⁷, O. Gueta ¹⁵⁴, C. Guicheney ³⁴, E. Guido ^{50a,50b}, T. Guillemain ¹¹⁶, S. Guindon ², U. Gul ⁵³, C. Gumpert ⁴⁴, J. Gunther ¹²⁷, J. Guo ³⁵, S. Gupta ¹¹⁹, P. Gutierrez ¹¹², N.G. Gutierrez Ortiz ⁵³, C. Gutsche ⁷⁷, N. Guttman ¹⁵⁴, C. Guyot ¹³⁷, C. Gwenlan ¹¹⁹, C.B. Gwilliam ⁷³, A. Haas ¹⁰⁹, C. Haber ¹⁵, H.K. Hadavand ⁸, N. Haddad ^{136e}, P. Haefner ²¹, S. Hageböck ²¹, Z. Hajduk ³⁹, H. Hakobyan ¹⁷⁸, M. Haleem ⁴², D. Hall ¹¹⁹, G. Halladjian ⁸⁹, K. Hamacher ¹⁷⁶, P. Hamal ¹¹⁴, K. Hamano ¹⁷⁰, M. Hamer ⁵⁴, A. Hamilton ^{146a}, S. Hamilton ¹⁶², G.N. Hamity ^{146c}, P.G. Hamnett ⁴², L. Han ^{33b}, K. Hanagaki ¹¹⁷, K. Hanawa ¹⁵⁶, M. Hance ¹⁵, P. Hanke ^{58a}, R. Hanna ¹³⁷, J.B. Hansen ³⁶, J.D. Hansen ³⁶, P.H. Hansen ³⁶, K. Hara ¹⁶¹, A.S. Hard ¹⁷⁴, T. Harenberg ¹⁷⁶, F. Hariri ¹¹⁶, S. Harkusha ⁹¹, D. Harper ⁸⁸, R.D. Harrington ⁴⁶, O.M. Harris ¹³⁹, P.F. Harrison ¹⁷¹, F. Hartjes ¹⁰⁶, M. Hasegawa ⁶⁶, S. Hasegawa ¹⁰², Y. Hasegawa ¹⁴¹, A. Hasib ¹¹², S. Hassani ¹³⁷, S. Haug ¹⁷, M. Hauschild ³⁰, R. Hauser ⁸⁹, M. Havranek ¹²⁶, C.M. Hawkes ¹⁸, R.J. Hawkings ³⁰, A.D. Hawkins ⁸⁰, T. Hayashi ¹⁶¹, D. Hayden ⁸⁹, C.P. Hays ¹¹⁹, H.S. Hayward ⁷³, S.J. Haywood ¹³⁰, S.J. Head ¹⁸, T. Heck ⁸², V. Hedberg ⁸⁰, L. Heelan ⁸, S. Heim ¹²¹, T. Heim ¹⁷⁶, B. Heinemann ¹⁵, L. Heinrich ¹⁰⁹, J. Hejbal ¹²⁶, L. Helary ²², C. Heller ⁹⁹, M. Heller ³⁰, S. Hellman ^{147a,147b}, D. Hellmich ²¹, C. Helsens ³⁰, J. Henderson ¹¹⁹, R.C.W. Henderson ⁷¹, Y. Heng ¹⁷⁴, C. Hengler ⁴², A. Henrichs ¹⁷⁷, A.M. Henriques Correia ³⁰, S. Henrot-Versille ¹¹⁶, C. Hensel ⁵⁴, G.H. Herbert ¹⁶, Y. Hernández Jiménez ¹⁶⁸, R. Herrberg-Schubert ¹⁶, G. Herten ⁴⁸, R. Hertenberger ⁹⁹, L. Hervas ³⁰, G.G. Hesketh ⁷⁷, N.P. Hessey ¹⁰⁶, R. Hickling ⁷⁵, E. Higón-Rodríguez ¹⁶⁸, E. Hill ¹⁷⁰, J.C. Hill ²⁸, K.H. Hiller ⁴², S. Hillert ²¹, S.J. Hillier ¹⁸, I. Hinchliffe ¹⁵, E. Hines ¹²¹, M. Hirose ¹⁵⁸, D. Hirschbuehl ¹⁷⁶, J. Hobbs ¹⁴⁹, N. Hod ¹⁰⁶, M.C. Hodgkinson ¹⁴⁰, P. Hodgson ¹⁴⁰, A. Hoecker ³⁰, M.R. Hoferkamp ¹⁰⁴, F. Hoenig ⁹⁹, J. Hoffman ⁴⁰, D. Hoffmann ⁸⁴, J.I. Hofmann ^{58a}, M. Hohlfield ⁸², T.R. Holmes ¹⁵, T.M. Hong ¹²¹, L. Hooft van Huysduynen ¹⁰⁹, Y. Horii ¹⁰², J.-Y. Hostachy ⁵⁵, S. Hou ¹⁵², A. Hoummada ^{136a}, J. Howard ¹¹⁹, J. Howarth ⁴², M. Hrabovsky ¹¹⁴, I. Hristova ¹⁶, J. Hrivnac ¹¹⁶, T. Hryn'ova ⁵, C. Hsu ^{146c}, P.J. Hsu ⁸², S.-C. Hsu ¹³⁹, D. Hu ³⁵, X. Hu ²⁵, Y. Huang ⁴², Z. Hubacek ³⁰, F. Hubaut ⁸⁴, F. Huegging ²¹, T.B. Huffman ¹¹⁹, E.W. Hughes ³⁵, G. Hughes ⁷¹, M. Huhtinen ³⁰, T.A. Hülsing ⁸², M. Hurwitz ¹⁵, N. Huseynov ^{64,b}, J. Huston ⁸⁹, J. Huth ⁵⁷, G. Iacobucci ⁴⁹, G. Iakovidis ¹⁰, I. Ibragimov ¹⁴², L. Iconomidou-Fayard ¹¹⁶, E. Ideal ¹⁷⁷, P. Iengo ^{103a}, O. Igonkina ¹⁰⁶, T. Iizawa ¹⁷², Y. Ikegami ⁶⁵, K. Ikematsu ¹⁴², M. Ikeno ⁶⁵, Y. Ilchenko ^{31,o}, D. Iliadis ¹⁵⁵, N. Ilic ¹⁵⁹, Y. Inamaru ⁶⁶, T. Ince ¹⁰⁰, P. Ioannou ⁹, M. Iodice ^{135a}, K. Iordanidou ⁹, V. Ippolito ⁵⁷, A. Irles Quiles ¹⁶⁸, C. Isaksson ¹⁶⁷, M. Ishino ⁶⁷, M. Ishitsuka ¹⁵⁸, R. Ishmukhametov ¹¹⁰, C. Issever ¹¹⁹, S. Istin ^{19a}, J.M. Iturbe Ponce ⁸³, R. Iuppa ^{134a,134b}, J. Ivarsson ⁸⁰, W. Iwanski ³⁹, H. Iwasaki ⁶⁵, J.M. Izen ⁴¹, V. Izzo ^{103a}, B. Jackson ¹²¹, M. Jackson ⁷³, P. Jackson ¹, M.R. Jaekel ³⁰, V. Jain ², K. Jakobs ⁴⁸, S. Jakobsen ³⁰, T. Jakoubek ¹²⁶, J. Jakubek ¹²⁷, D.O. Jamin ¹⁵², D.K. Jana ⁷⁸, E. Jansen ⁷⁷, H. Jansen ³⁰, J. Janssen ²¹, M. Janus ¹⁷¹, G. Jarlskog ⁸⁰, N. Javadov ^{64,b}, T. Javůrek ⁴⁸, L. Jeanty ¹⁵, J. Jejelava ^{51a,p}, G.-Y. Jeng ¹⁵¹, D. Jennens ⁸⁷, P. Jenni ^{48,q}, J. Jentzsch ⁴³, C. Jeske ¹⁷¹, S. Jézéquel ⁵, H. Ji ¹⁷⁴, J. Jia ¹⁴⁹, Y. Jiang ^{33b}, M. Jimenez Belenguer ⁴², S. Jin ^{33a}, A. Jinaru ^{26a}, O. Jinnouchi ¹⁵⁸, M.D. Joergensen ³⁶, K.E. Johansson ^{147a,147b}, P. Johansson ¹⁴⁰, K.A. Johns ⁷,

K. Jon-And ^{147a,147b}, G. Jones ¹⁷¹, R.W.L. Jones ⁷¹, T.J. Jones ⁷³, J. Jongmanns ^{58a}, P.M. Jorge ^{125a,125b}, K.D. Joshi ⁸³, J. Jovicevic ¹⁴⁸, X. Ju ¹⁷⁴, C.A. Jung ⁴³, R.M. Jungst ³⁰, P. Jussel ⁶¹, A. Juste Rozas ^{12,n}, M. Kaci ¹⁶⁸, A. Kaczmarska ³⁹, M. Kado ¹¹⁶, H. Kagan ¹¹⁰, M. Kagan ¹⁴⁴, E. Kajomovitz ⁴⁵, C.W. Kalderon ¹¹⁹, S. Kama ⁴⁰, A. Kamenshchikov ¹²⁹, N. Kanaya ¹⁵⁶, M. Kaneda ³⁰, S. Kaneti ²⁸, V.A. Kantserov ⁹⁷, J. Kanzaki ⁶⁵, B. Kaplan ¹⁰⁹, A. Kapliy ³¹, D. Kar ⁵³, K. Karakostas ¹⁰, N. Karastathis ¹⁰, M. Karnevskiy ⁸², S.N. Karpov ⁶⁴, Z.M. Karpova ⁶⁴, K. Karthik ¹⁰⁹, V. Kartvelishvili ⁷¹, A.N. Karyukhin ¹²⁹, L. Kashif ¹⁷⁴, G. Kasieczka ^{58b}, R.D. Kass ¹¹⁰, A. Kastanas ¹⁴, Y. Kataoka ¹⁵⁶, A. Katre ⁴⁹, J. Katzy ⁴², V. Kaushik ⁷, K. Kawagoe ⁶⁹, T. Kawamoto ¹⁵⁶, G. Kawamura ⁵⁴, S. Kazama ¹⁵⁶, V.F. Kazanin ¹⁰⁸, M.Y. Kazarinov ⁶⁴, R. Keeler ¹⁷⁰, R. Kehoe ⁴⁰, M. Keil ⁵⁴, J.S. Keller ⁴², J.J. Kempster ⁷⁶, H. Keoshkerian ⁵, O. Kepka ¹²⁶, B.P. Kerševan ⁷⁴, S. Kersten ¹⁷⁶, K. Kessoku ¹⁵⁶, J. Keung ¹⁵⁹, F. Khalil-zada ¹¹, H. Khandanyan ^{147a,147b}, A. Khanov ¹¹³, A. Khodinov ⁹⁷, A. Khomich ^{58a}, T.J. Khoo ²⁸, G. Khorauli ²¹, A. Khoroshilov ¹⁷⁶, V. Khovanskiy ⁹⁶, E. Khramov ⁶⁴, J. Khubua ^{51b}, H.Y. Kim ⁸, H. Kim ^{147a,147b}, S.H. Kim ¹⁶¹, N. Kimura ¹⁷², O. Kind ¹⁶, B.T. King ⁷³, M. King ¹⁶⁸, R.S.B. King ¹¹⁹, S.B. King ¹⁶⁹, J. Kirk ¹³⁰, A.E. Kiryunin ¹⁰⁰, T. Kishimoto ⁶⁶, D. Kisielewska ^{38a}, F. Kiss ⁴⁸, T. Kittelmann ¹²⁴, K. Kiuchi ¹⁶¹, E. Kladiva ^{145b}, M. Klein ⁷³, U. Klein ⁷³, K. Kleinknecht ⁸², P. Klimek ^{147a,147b}, A. Klimentov ²⁵, R. Klingenberg ⁴³, J.A. Klinger ⁸³, T. Klioutchnikova ³⁰, P.F. Klok ¹⁰⁵, E.-E. Kluge ^{58a}, P. Kluit ¹⁰⁶, S. Kluth ¹⁰⁰, E. Kneringer ⁶¹, E.B.F.G. Knoops ⁸⁴, A. Knue ⁵³, D. Kobayashi ¹⁵⁸, T. Kobayashi ¹⁵⁶, M. Kobel ⁴⁴, M. Kocian ¹⁴⁴, P. Kodys ¹²⁸, P. Koevesarki ²¹, T. Koffas ²⁹, E. Koffeman ¹⁰⁶, L.A. Kogan ¹¹⁹, S. Kohlmann ¹⁷⁶, Z. Kohout ¹²⁷, T. Kohriki ⁶⁵, T. Koi ¹⁴⁴, H. Kolanoski ¹⁶, I. 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Lee ¹⁰⁶, J.S.H. Lee ¹¹⁷, S.C. Lee ¹⁵², L. Lee ¹, G. Lefebvre ⁷⁹, M. Lefebvre ¹⁷⁰, F. Legger ⁹⁹, C. Leggett ¹⁵, A. Lehan ⁷³, M. Lehmacher ²¹, G. Lehmann Miotto ³⁰, X. Lei ⁷, W.A. Leight ²⁹, A. Leisos ¹⁵⁵, A.G. Leister ¹⁷⁷, M.A.L. Leite ^{24d}, R. Leitner ¹²⁸, D. Lellouch ¹⁷³, B. Lemmer ⁵⁴, K.J.C. Leney ⁷⁷, T. Lenz ²¹, G. Lenzen ¹⁷⁶, B. Lenzi ³⁰, R. Leone ⁷, S. Leone ^{123a,123b}, K. Leonhardt ⁴⁴, C. Leonidopoulos ⁴⁶, S. Leontsinis ¹⁰, C. Leroy ⁹⁴, C.G. Lester ²⁸, C.M. Lester ¹²¹, M. Levchenko ¹²², J. Levêque ⁵, D. Levin ⁸⁸, L.J. Levinson ¹⁷³, M. Levy ¹⁸, A. Lewis ¹¹⁹, G.H. Lewis ¹⁰⁹, A.M. Leyko ²¹, M. Leyton ⁴¹, B. Li ^{33b,u}, B. Li ⁸⁴, H. Li ¹⁴⁹, H.L. Li ³¹, L. Li ⁴⁵, L. Li ^{33e}, S. Li ⁴⁵, Y. Li ^{33c,v}, Z. Liang ¹³⁸, H. Liao ³⁴, B. Liberti ^{134a}, P. Lichard ³⁰, K. Lie ¹⁶⁶, J. Liebal ²¹, W. Liebig ¹⁴, C. Limbach ²¹, A. Limosani ⁸⁷, S.C. Lin ^{152,w}, T.H. Lin ⁸², F. Linde ¹⁰⁶, B.E. Lindquist ¹⁴⁹, J.T. Linnemann ⁸⁹, E. Lipeles ¹²¹, A. Lipniacka ¹⁴, M. Lisovyi ⁴², T.M. Liss ¹⁶⁶, D. Lissauer ²⁵, A. Lister ¹⁶⁹, A.M. Litke ¹³⁸, B. Liu ¹⁵², D. Liu ¹⁵², J.B. Liu ^{33b}, K. Liu ^{33b,x}, L. Liu ⁸⁸, M. Liu ⁴⁵, M. Liu ^{33b}, Y. Liu ^{33b}, M. Livan ^{120a,120b}, S.S.A. Livermore ¹¹⁹, A. Lleres ⁵⁵, J. Llorente Merino ⁸¹, S.L. Lloyd ⁷⁵, F. Lo Sterzo ¹⁵², E. Lobodzinska ⁴², P. Loch ⁷, W.S. Lockman ¹³⁸, T. Loddenkoetter ²¹, F.K. Loebinger ⁸³, A.E. Loevschall-Jensen ³⁶, A. Loginov ¹⁷⁷, T. Lohse ¹⁶, K. Lohwasser ⁴², M. Lokajicek ¹²⁶, V.P. Lombardo ⁵, B.A. Long ²², J.D. Long ⁸⁸, R.E. Long ⁷¹, L. Lopes ^{125a}, D. Lopez Mateos ⁵⁷, B. Lopez Paredes ¹⁴⁰, I. Lopez Paz ¹², J. Lorenz ⁹⁹, N. Lorenzo Martinez ⁶⁰, M. Losada ¹⁶³, P. Loscutoff ¹⁵, X. Lou ⁴¹, A. Lounis ¹¹⁶,

J. Love⁶, P.A. Love⁷¹, A.J. Lowe^{144,e}, F. Lu^{33a}, N. Lu⁸⁸, H.J. Lubatti¹³⁹, C. Luci^{133a,133b}, A. Lucotte⁵⁵, F. Luehring⁶⁰, W. Lukas⁶¹, L. Luminari^{133a}, O. Lundberg^{147a,147b}, B. Lund-Jensen¹⁴⁸, M. Lungwitz⁸², D. Lynn²⁵, R. Lysak¹²⁶, E. Lytken⁸⁰, H. Ma²⁵, L.L. Ma^{33d}, G. Maccarrone⁴⁷, A. Macchiolo¹⁰⁰, J. Machado Miguens^{125a,125b}, D. Macina³⁰, D. Madaffari⁸⁴, R. Madar⁴⁸, H.J. Maddocks⁷¹, W.F. Mader⁴⁴, A. Madsen¹⁶⁷, M. Maeno⁸, T. Maeno²⁵, E. Magradze⁵⁴, K. Mahboubi⁴⁸, J. Mahlstedt¹⁰⁶, S. Mahmoud⁷³, C. Maiani¹³⁷, C. Maidantchik^{24a}, A.A. Maier¹⁰⁰, A. Maio^{125a,125b,125d}, S. Majewski¹¹⁵, Y. Makida⁶⁵, N. Makovec¹¹⁶, P. Mal^{137,y}, B. Malaescu⁷⁹, Pa. Malecki³⁹, V.P. Maleev¹²², F. Malek⁵⁵, U. Mallik⁶², D. Malon⁶, C. Malone¹⁴⁴, S. Maltezos¹⁰, V.M. Malyshev¹⁰⁸, S. Malyukov³⁰, J. Mamuzic^{13b}, B. Mandelli³⁰, L. Mandelli^{90a}, I. Mandić⁷⁴, R. Mandrysch⁶², J. Maneira^{125a,125b}, A. Manfredini¹⁰⁰, L. Manhaes de Andrade Filho^{24b}, J.A. Manjarres Ramos^{160b}, A. Mann⁹⁹, P.M. Manning¹³⁸, A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁷, R. Mantifel⁸⁶, L. Mapelli³⁰, L. March¹⁶⁸, J.F. Marchand²⁹, G. Marchiori⁷⁹, M. Marcisovsky¹²⁶, C.P. Marino¹⁷⁰, M. Marjanovic^{13a}, C.N. Marques^{125a}, F. Marroquim^{24a}, S.P. Marsden⁸³, Z. Marshall¹⁵, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁸, B. Martin³⁰, B. Martin⁸⁹, T.A. Martin¹⁷¹, V.J. Martin⁴⁶, B. Martin dit Latour¹⁴, H. Martinez¹³⁷, M. Martinez^{12,n}, S. Martin-Haugh¹³⁰, A.C. Martyniuk⁷⁷, M. Marx¹³⁹, F. Marzano^{133a}, A. Marzin³⁰, L. Masetti⁸², T. Mashimo¹⁵⁶, R. Mashinistov⁹⁵, J. Masik⁸³, A.L. Maslennikov¹⁰⁸, I. Massa^{20a,20b}, L. Massa^{20a,20b}, N. Massol⁵, P. Mastrandrea¹⁴⁹, A. Mastroberardino^{37a,37b}, T. Masubuchi¹⁵⁶, P. Mättig¹⁷⁶, J. Mattmann⁸², J. Maurer^{26a}, S.J. Maxfield⁷³, D.A. Maximov^{108,t}, R. Mazini¹⁵², L. Mazzaferro^{134a,134b}, G. Mc Goldrick¹⁵⁹, S.P. Mc Kee⁸⁸, A. McCarn⁸⁸, R.L. McCarthy¹⁴⁹, T.G. McCarthy²⁹, N.A. McCubbin¹³⁰, K.W. McFarlane^{56,*}, J.A. Mcfayden⁷⁷, G. Mchedlidze⁵⁴, S.J. McMahon¹³⁰, R.A. McPherson^{170,i}, A. Meade⁸⁵, J. Mechnich¹⁰⁶, M. Medinnis⁴², S. Meehan³¹, S. Mehlhase⁹⁹, A. Mehta⁷³, K. Meier^{58a}, C. Meineck⁹⁹, B. Meirose⁸⁰, C. Melachrinos³¹, B.R. Mellado Garcia^{146c}, F. Meloni¹⁷, A. Mengarelli^{20a,20b}, S. Menke¹⁰⁰, E. Meoni¹⁶², K.M. Mercurio⁵⁷, S. Mergelmeyer²¹, N. Meric¹³⁷, P. Mermod⁴⁹, L. Merola^{103a,103b}, C. Meroni^{90a}, F.S. Merritt³¹, H. Merritt¹¹⁰, A. Messina^{30,z}, J. Metcalfe²⁵, A.S. Mete¹⁶⁴, C. Meyer⁸², C. Meyer¹²¹, J.-P. Meyer¹³⁷, J. Meyer³⁰, R.P. Middleton¹³⁰, S. Migas⁷³, L. Mijović²¹, G. Mikenberg¹⁷³, M. Mikestikova¹²⁶, M. Mikuz⁷⁴, A. Milic³⁰, D.W. Miller³¹, C. Mills⁴⁶, A. Milov¹⁷³, D.A. Milstead^{147a,147b}, D. Milstein¹⁷³, A.A. Minaenko¹²⁹, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁹, B. Mindur^{38a}, M. Mineev⁶⁴, Y. Ming¹⁷⁴, L.M. Mir¹², G. Mirabelli^{133a}, T. Mitani¹⁷², J. Mitrevski⁹⁹, V.A. Mitsou¹⁶⁸, S. Mitsui⁶⁵, A. Miucci⁴⁹, P.S. Miyagawa¹⁴⁰, J.U. Mjörnmark⁸⁰, T. Moa^{147a,147b}, K. Mochizuki⁸⁴, S. Mohapatra³⁵, W. Mohr⁴⁸, S. Molander^{147a,147b}, R. Moles-Valls¹⁶⁸, K. Mönig⁴², C. Monini⁵⁵, J. Monk³⁶, E. Monnier⁸⁴, J. Montejo Berlingen¹², F. Monticelli⁷⁰, S. Monzani^{133a,133b}, R.W. Moore³, N. Morange⁶², D. Moreno⁸², M. Moreno Llácer⁵⁴, P. Morettini^{50a}, M. Morgenstern⁴⁴, M. Morii⁵⁷, S. Moritz⁸², A.K. Morley¹⁴⁸, G. Mornacchi³⁰, J.D. Morris⁷⁵, L. Morvaj¹⁰², H.G. Moser¹⁰⁰, M. Mosidze^{51b}, J. Moss¹¹⁰, K. Motohashi¹⁵⁸, R. Mount¹⁴⁴, E. Mountricha²⁵, S.V. Mouraviev^{95,*}, E.J.W. Moyse⁸⁵, S. Muanza⁸⁴, R.D. Mudd¹⁸, F. Mueller^{58a}, J. Mueller¹²⁴, K. Mueller²¹, T. Mueller²⁸, T. Mueller⁸², D. Muenstermann⁴⁹, Y. Munwes¹⁵⁴, J.A. Murillo Quijada¹⁸, W.J. Murray^{171,130}, H. Musheghyan⁵⁴, E. Musto¹⁵³, A.G. Myagkov^{129,aa}, M. Myska¹²⁷, O. Nackenhorst⁵⁴, J. Nadal⁵⁴, K. Nagai⁶¹, R. Nagai¹⁵⁸, Y. Nagai⁸⁴, K. Nagano⁶⁵, A. Nagarkar¹¹⁰, Y. Nagasaka⁵⁹, M. Nagel¹⁰⁰, A.M. Nairz³⁰, Y. Nakahama³⁰, K. Nakamura⁶⁵, T. Nakamura¹⁵⁶, I. Nakano¹¹¹, H. Namasivayam⁴¹, G. Nanava²¹, R. Narayan^{58b}, T. Nattermann²¹, T. Naumann⁴², G. Navarro¹⁶³, R. Nayyar⁷, H.A. Neal⁸⁸, P.Yu. Nechaeva⁹⁵, T.J. Neep⁸³, P.D. Nef¹⁴⁴, A. Negri^{120a,120b}, G. Negri³⁰, M. Negrini^{20a}, S. Nektarijevic⁴⁹, A. Nelson¹⁶⁴, T.K. Nelson¹⁴⁴, S. Nemecek¹²⁶, P. Nemethy¹⁰⁹, A.A. Nepomuceno^{24a}, M. Nessi^{30,ab}, M.S. Neubauer¹⁶⁶, M. Neumann¹⁷⁶, R.M. Neves¹⁰⁹, P. Nevski²⁵, P.R. Newman¹⁸, D.H. Nguyen⁶, R.B. Nickerson¹¹⁹, R. Nicolaidou¹³⁷, B. Nicquevert³⁰, J. Nielsen¹³⁸, N. Nikiforou³⁵, A. Nikiforov¹⁶, V. Nikolaenko^{129,aa}, I. Nikolic-Audit⁷⁹, K. Nikolics⁴⁹, K. Nikolopoulos¹⁸, P. Nilsson⁸, Y. Ninomiya¹⁵⁶, A. Nisati^{133a}, R. Nisius¹⁰⁰, T. Nobe¹⁵⁸, L. Nodulman⁶, M. Nomachi¹¹⁷, I. Nomidis²⁹, S. Norberg¹¹², M. Nordberg³⁰, O. Novgorodova⁴⁴, S. Nowak¹⁰⁰, M. Nozaki⁶⁵, L. Nozka¹¹⁴, K. Ntekas¹⁰, G. Nunes Hanninger⁸⁷, T. Nunnemann⁹⁹, E. Nurse⁷⁷, F. Nuti⁸⁷, B.J. O'Brien⁴⁶, F. O'grady⁷, D.C. O'Neil¹⁴³, V. O'Shea⁵³, F.G. Oakham^{29,d}, H. Oberlack¹⁰⁰, T. Obermann²¹, J. Ocariz⁷⁹, A. Ochi⁶⁶, M.I. Ochoa⁷⁷, S. Oda⁶⁹, S. Odaka⁶⁵, H. Ogren⁶⁰, A. Oh⁸³, S.H. Oh⁴⁵, C.C. Ohm¹⁵, H. Ohman¹⁶⁷, W. Okamura¹¹⁷, H. Okawa²⁵, Y. Okumura³¹, T. Okuyama¹⁵⁶, A. Olariu^{26a}, A.G. Olchevski⁶⁴, S.A. Olivares Pino⁴⁶, D. Oliveira Damazio²⁵, E. Oliver Garcia¹⁶⁸, A. Olszewski³⁹, J. Olszowska³⁹, A. Onofre^{125a,125e}, P.U.E. Onyisi^{31,o}, C.J. Oram^{160a},

M.J. Oreglia³¹, Y. Oren¹⁵⁴, D. Orestano^{135a,135b}, N. Orlando^{72a,72b}, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁹, B. Osculati^{50a,50b}, R. Ospanov¹²¹, G. Otero y Garzon²⁷, H. Otono⁶⁹, M. Ouchrif^{136d}, E.A. Ouellette¹⁷⁰, F. Ould-Saada¹¹⁸, A. Ouraou¹³⁷, K.P. Oussoren¹⁰⁶, Q. Ouyang^{33a}, A. Ovcharova¹⁵, M. Owen⁸³, V.E. Ozcan^{19a}, N. Ozturk⁸, K. Pachal¹¹⁹, A. Pacheco Pages¹², C. Padilla Aranda¹², M. Pagáčová⁴⁸, S. Pagan Griso¹⁵, E. Paganis¹⁴⁰, C. Pahl¹⁰⁰, F. Paige²⁵, P. Pais⁸⁵, K. Pajchel¹¹⁸, G. Palacino^{160b}, S. Palestini³⁰, M. Palka^{38b}, D. Pallin³⁴, A. Palma^{125a,125b}, J.D. Palmer¹⁸, Y.B. Pan¹⁷⁴, E. Panagiotopoulou¹⁰, J.G. Panduro Vazquez⁷⁶, P. Pani¹⁰⁶, N. Panikashvili⁸⁸, S. Panitkin²⁵, D. Pantea^{26a}, L. Paolozzi^{134a,134b}, Th.D. Papadopoulou¹⁰, K. Papageorgiou^{155,l}, A. Paramonov⁶, D. Paredes Hernandez³⁴, M.A. Parker²⁸, F. Parodi^{50a,50b}, J.A. Parsons³⁵, U. Parzefall⁴⁸, E. Pasqualucci^{133a}, S. Passaggio^{50a}, A. Passeri^{135a}, F. Pastore^{135a,135b,*}, Fr. Pastore⁷⁶, G. Pásztor²⁹, S. Pataraiia¹⁷⁶, N.D. Patel¹⁵¹, J.R. Pater⁸³, S. Patricelli^{103a,103b}, T. Pauly³⁰, J. Pearce¹⁷⁰, L.E. Pedersen³⁶, M. Pedersen¹¹⁸, S. Pedraza Lopez¹⁶⁸, R. Pedro^{125a,125b}, S.V. Peleganchuk¹⁰⁸, D. Pelikan¹⁶⁷, H. Peng^{33b}, B. Penning³¹, J. Penwell⁶⁰, D.V. Perepelitsa²⁵, E. Perez Codina^{160a}, M.T. Pérez García-Están¹⁶⁸, V. Perez Reale³⁵, L. Perini^{90a,90b}, H. Pernegger³⁰, R. Perrino^{72a}, R. Peschke⁴², V.D. Peshekhonov⁶⁴, K. Peters³⁰, R.F.Y. Peters⁸³, B.A. Petersen³⁰, T.C. Petersen³⁶, E. Petit⁴², A. Petridis^{147a,147b}, C. Petridou¹⁵⁵, E. Petrolo^{133a}, F. Petrucci^{135a,135b}, N.E. Pettersson¹⁵⁸, R. Pezoa^{32b}, P.W. Phillips¹³⁰, G. Piacquadio¹⁴⁴, E. Pianori¹⁷¹, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{20a,20b}, R. Piegaia²⁷, D.T. Pignotti¹¹⁰, J.E. Pilcher³¹, A.D. Pilkington⁷⁷, J. Pina^{125a,125b,125d}, M. Pinamonti^{165a,165c,ac}, A. Pinder¹¹⁹, J.L. Pinfold³, A. Pingel³⁶, B. Pinto^{125a}, S. Pires⁷⁹, M. Pitt¹⁷³, C. Pizio^{90a,90b}, L. Plazak^{145a}, M.-A. Pleier²⁵, V. Pleskot¹²⁸, E. Plotnikova⁶⁴, P. Plucinski^{147a,147b}, S. Poddar^{58a}, F. Podlyski³⁴, R. Poettgen⁸², L. Poggioli¹¹⁶, D. Pohl²¹, M. Pohl⁴⁹, G. Polesello^{120a}, A. Policicchio^{37a,37b}, R. Polifka¹⁵⁹, A. Polini^{20a}, C.S. Pollard⁴⁵, V. Polychronakos²⁵, K. Pommès³⁰, L. Pontecorvo^{133a}, B.G. Pope⁸⁹, G.A. Popeneciu^{26b}, D.S. Popovic^{13a}, A. Poppleton³⁰, X. Portell Bueso¹², S. Pospisil¹²⁷, K. Potamianos¹⁵, I.N. Potrap⁶⁴, C.J. Potter¹⁵⁰, C.T. Potter¹¹⁵, G. Poulard³⁰, J. Poveda⁶⁰, V. Pozdnyakov⁶⁴, P. Pralavorio⁸⁴, A. Pranko¹⁵, S. Prasad³⁰, R. Pravahan⁸, S. Prell⁶³, D. Price⁸³, J. Price⁷³, L.E. Price⁶, D. Prieur¹²⁴, M. Primavera^{72a}, M. Proissl⁴⁶, K. Prokofiev⁴⁷, F. Prokoshin^{32b}, E. Protopapadaki¹³⁷, S. Protopopescu²⁵, J. Proudfoot⁶, M. Przybycien^{38a}, H. Przysiezniak⁵, E. Ptacek¹¹⁵, D. Puddu^{135a,135b}, E. Pueschel⁸⁵, D. Poldon¹⁴⁹, M. Purohit^{25,ad}, P. Puzo¹¹⁶, J. Qian⁸⁸, G. Qin⁵³, Y. Qin⁸³, A. Quadt⁵⁴, D.R. Quarrie¹⁵, W.B. Quayle^{165a,165b}, M. Queitsch-Maitland⁸³, D. Quilty⁵³, A. Qureshi^{160b}, V. Radeka²⁵, V. Radescu⁴², S.K. Radhakrishnan¹⁴⁹, P. Radloff¹¹⁵, P. Rados⁸⁷, F. Ragusa^{90a,90b}, G. Rahal¹⁷⁹, S. Rajagopalan²⁵, M. Rammensee³⁰, A.S. Randle-Conde⁴⁰, C. Rangel-Smith¹⁶⁷, K. Rao¹⁶⁴, F. Rauscher⁹⁹, T.C. Rave⁴⁸, T. Ravenscroft⁵³, M. Raymond³⁰, A.L. Read¹¹⁸, N.P. Readioff⁷³, D.M. Rebuzzi^{120a,120b}, A. Redelbach¹⁷⁵, G. Redlinger²⁵, R. Reece¹³⁸, K. Reeves⁴¹, L. Rehnisch¹⁶, H. Reisin²⁷, M. Relich¹⁶⁴, C. Rembser³⁰, H. Ren^{33a}, Z.L. Ren¹⁵², A. Renaud¹¹⁶, M. Rescigno^{133a}, S. Resconi^{90a}, O.L. Rezanova^{108,t}, P. Reznicek¹²⁸, R. Rezvani⁹⁴, R. Richter¹⁰⁰, M. Ridel⁷⁹, P. Rieck¹⁶, J. Rieger⁵⁴, M. Rijssenbeek¹⁴⁹, A. Rimoldi^{120a,120b}, L. Rinaldi^{20a}, E. Ritsch⁶¹, I. Riu¹², F. Rizatdinova¹¹³, E. Rizvi⁷⁵, S.H. Robertson^{86,i}, A. Robichaud-Veronneau⁸⁶, D. Robinson²⁸, J.E.M. Robinson⁸³, A. Robson⁵³, C. Roda^{123a,123b}, L. Rodrigues³⁰, S. Roe³⁰, O. Røhne¹¹⁸, S. Rolli¹⁶², A. Romaniouk⁹⁷, M. Romano^{20a,20b}, E. Romero Adam¹⁶⁸, N. Rompotis¹³⁹, M. Ronzani⁴⁸, L. Roos⁷⁹, E. Ros¹⁶⁸, S. Rosati^{133a}, K. Rosbach⁴⁹, M. Rose⁷⁶, P. Rose¹³⁸, P.L. Rosendahl¹⁴, O. Rosenthal¹⁴², V. Rossetti^{147a,147b}, E. Rossi^{103a,103b}, L.P. Rossi^{50a}, R. Rosten¹³⁹, M. Rotaru^{26a}, I. Roth¹⁷³, J. Rothberg¹³⁹, D. Rousseau¹¹⁶, C.R. Royon¹³⁷, A. Rozanov⁸⁴, Y. Rozen¹⁵³, X. Ruan^{146c}, F. Rubbo¹², I. Rubinskiy⁴², V.I. Rud⁹⁸, C. Rudolph⁴⁴, M.S. Rudolph¹⁵⁹, F. Rühr⁴⁸, A. Ruiz-Martinez³⁰, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, A. Ruschke⁹⁹, J.P. Rutherford⁷, N. Ruthmann⁴⁸, Y.F. Ryabov¹²², M. Rybar¹²⁸, G. Rybkin¹¹⁶, N.C. Ryder¹¹⁹, A.F. Saavedra¹⁵¹, S. Sacerdoti²⁷, A. Saddique³, I. Sadeh¹⁵⁴, H.F.-W. Sadrozinski¹³⁸, R. Sadykov⁶⁴, F. Safai Tehrani^{133a}, H. Sakamoto¹⁵⁶, Y. Sakurai¹⁷², G. Salamanna^{135a,135b}, A. Salamon^{134a}, M. Saleem¹¹², D. Salek¹⁰⁶, P.H. Sales De Bruin¹³⁹, D. Salihagic¹⁰⁰, A. Salnikov¹⁴⁴, J. Salt¹⁶⁸, D. Salvatore^{37a,37b}, F. Salvatore¹⁵⁰, A. Salvucci¹⁰⁵, A. Salzburger³⁰, D. Sampsonidis¹⁵⁵, A. Sanchez^{103a,103b}, J. Sánchez¹⁶⁸, V. Sanchez Martinez¹⁶⁸, H. Sandaker¹⁴, R.L. Sandbach⁷⁵, H.G. Sander⁸², M.P. Sanders⁹⁹, M. Sandhoff¹⁷⁶, T. Sandoval²⁸, C. Sandoval¹⁶³, R. Sandstroem¹⁰⁰, D.P.C. Sankey¹³⁰, A. Sansoni⁴⁷, C. Santoni³⁴, R. Santonico^{134a,134b}, H. Santos^{125a}, I. Santoyo Castillo¹⁵⁰, K. Sapp¹²⁴, A. Saponov⁶⁴, J.G. Saraiva^{125a,125d}, B. Sarrazin²¹, G. Sartisohn¹⁷⁶, O. Sasaki⁶⁵, Y. Sasaki¹⁵⁶, G. Sauvage^{5,*}, E. Sauvan⁵, P. Savard^{159,d}, D.O. Savu³⁰,

C. Sawyer¹¹⁹, L. Sawyer^{78,m}, D.H. Saxon⁵³, J. Saxon¹²¹, C. Sbarra^{20a}, A. Sbrizzi³, T. Scanlon⁷⁷, D.A. Scannicchio¹⁶⁴, M. Scarcella¹⁵¹, V. Scarfone^{37a,37b}, J. Schaarschmidt¹⁷³, P. Schacht¹⁰⁰, D. Schaefer³⁰, R. Schaefer⁴², S. Schaepe²¹, S. Schaetzel^{58b}, U. Schäfer⁸², A.C. Schaffer¹¹⁶, D. Schaile⁹⁹, R.D. Schamberger¹⁴⁹, V. Scharf^{58a}, V.A. Schegelsky¹²², D. Scheirich¹²⁸, M. Schernau¹⁶⁴, M.I. Scherzer³⁵, C. Schiavi^{50a,50b}, J. Schieck⁹⁹, C. Schillo⁴⁸, M. Schioppa^{37a,37b}, S. Schlenker³⁰, E. Schmidt⁴⁸, K. Schmieden³⁰, C. Schmitt⁸², S. Schmitt^{58b}, B. Schneider¹⁷, Y.J. Schnellbach⁷³, U. Schnoor⁴⁴, L. Schoeffel¹³⁷, A. Schoening^{58b}, B.D. Schoenrock⁸⁹, A.L.S. Schorlemmer⁵⁴, M. Schott⁸², D. Schouten^{160a}, J. Schovancova²⁵, S. Schramm¹⁵⁹, M. Schreyer¹⁷⁵, C. Schroeder⁸², N. Schuh⁸², M.J. Schultens²¹, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁶, M. Schumacher⁴⁸, B.A. Schumm¹³⁸, Ph. Schune¹³⁷, C. Schwanenberger⁸³, A. Schwartzman¹⁴⁴, Ph. Schwegler¹⁰⁰, Ph. Schwemling¹³⁷, R. Schwienhorst⁸⁹, J. Schwindling¹³⁷, T. Schwindt²¹, M. Schwoerer⁵, F.G. Sciaccia¹⁷, E. Scifo¹¹⁶, G. Sciolla²³, W.G. Scott¹³⁰, F. Scuri^{123a,123b}, F. Scutti²¹, J. Searcy⁸⁸, G. Sedov⁴², E. Sedykh¹²², S.C. Seidel¹⁰⁴, A. Seiden¹³⁸, F. Seifert¹²⁷, J.M. Seixas^{24a}, G. Sekhniaidze^{103a}, S.J. Sekula⁴⁰, K.E. Selbach⁴⁶, D.M. Seliverstov^{122,*}, G. Sellers⁷³, N. Semprini-Cesari^{20a,20b}, C. Serfon³⁰, L. Serin¹¹⁶, L. Serkin⁵⁴, T. Serre⁸⁴, R. Seuster^{160a}, H. Severini¹¹², T. Sfiligoi⁷⁴, F. Sforza¹⁰⁰, A. Sfyrla³⁰, E. Shabalina⁵⁴, M. Shamim¹¹⁵, L.Y. Shan^{33a}, R. Shang¹⁶⁶, J.T. Shank²², M. Shapiro¹⁵, P.B. Shatalov⁹⁶, K. Shaw^{165a,165b}, C.Y. Shehu¹⁵⁰, P. Sherwood⁷⁷, L. Shi^{152,ae}, S. Shimizu⁶⁶, C.O. Shimmin¹⁶⁴, M. Shimojima¹⁰¹, M. Shiyakova⁶⁴, A. Shmeleva⁹⁵, M.J. Shochet³¹, D. Short¹¹⁹, S. Shrestha⁶³, E. Shulga⁹⁷, M.A. Shupe⁷, S. Shushkevich⁴², P. Sicho¹²⁶, O. Sidiropoulou¹⁵⁵, D. Sidorov¹¹³, A. Sidoti^{133a}, F. Siegert⁴⁴, Dj. Sijacki^{13a}, J. Silva^{125a,125d}, Y. Silver¹⁵⁴, D. Silverstein¹⁴⁴, S.B. Silverstein^{147a}, V. Simak¹²⁷, O. Simard⁵, Lj. Simic^{13a}, S. Simion¹¹⁶, E. Simioni⁸², B. Simmons⁷⁷, R. Simoniello^{90a,90b}, M. Simonyan³⁶, P. Sinervo¹⁵⁹, N.B. Sinev¹¹⁵, V. Sipica¹⁴², G. Siragusa¹⁷⁵, A. Sircar⁷⁸, A.N. Sisakyan^{64,*}, S.Yu. Sivoklov⁹⁸, J. Sjölin^{147a,147b}, T.B. Sjursen¹⁴, H.P. Skottowe⁵⁷, K.Yu. Skovpen¹⁰⁸, P. Skubic¹¹², M. Slater¹⁸, T. Slavicek¹²⁷, K. Sliwa¹⁶², V. Smakhtin¹⁷³, B.H. Smart⁴⁶, L. Smestad¹⁴, S.Yu. Smirnov⁹⁷, Y. Smirnov⁹⁷, L.N. Smirnova^{98,af}, O. Smirnova⁸⁰, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁵, G. Snidero⁷⁵, S. Snyder²⁵, R. Sobie^{170,i}, F. Socher⁴⁴, A. Soffer¹⁵⁴, D.A. Soh^{152,ae}, C.A. Solans³⁰, M. Solar¹²⁷, J. Solc¹²⁷, E.Yu. Soldatov⁹⁷, U. Soldevila¹⁶⁸, A.A. Solodkov¹²⁹, A. Soloshenko⁶⁴, O.V. Solovyanov¹²⁹, V. Solovyev¹²², P. Sommer⁴⁸, H.Y. Song^{33b}, N. Soni¹, A. Sood¹⁵, A. Sopczak¹²⁷, B. Sopko¹²⁷, V. Sopko¹²⁷, V. Sorin¹², M. Sosebee⁸, R. Soualah^{165a,165c}, P. Soueid⁹⁴, A.M. Soukharev¹⁰⁸, D. South⁴², S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, W.R. Spearman⁵⁷, F. Spettel¹⁰⁰, R. Spighi^{20a}, G. Spigo³⁰, L.A. Spiller⁸⁷, M. Spousta¹²⁸, T. Spreitzer¹⁵⁹, B. Spurlock⁸, R.D. St. Denis^{53,*}, S. Staerz⁴⁴, J. Stahlman¹²¹, R. Stamen^{58a}, S. Stamm¹⁶, E. Stanecka³⁹, R.W. Stanek⁶, C. Stancu^{135a}, M. Stancu-Bellu⁴², M.M. Stanitzki⁴², S. Stapnes¹¹⁸, E.A. Starchenko¹²⁹, J. Stark⁵⁵, P. Staroba¹²⁶, P. Starovoitov⁴², R. Staszewski³⁹, P. Stavina^{145a,*}, P. Steinberg²⁵, B. Stelzer¹⁴³, H.J. Stelzer³⁰, O. Stelzer-Chilton^{160a}, H. Stenzel⁵², S. Stern¹⁰⁰, G.A. Stewart⁵³, J.A. Stillings²¹, M.C. Stockton⁸⁶, M. Stoebe⁸⁶, G. Stoica^{26a}, P. Stolte⁵⁴, S. Stonjek¹⁰⁰, A.R. Stradling⁸, A. Straessner⁴⁴, M.E. Stramaglia¹⁷, J. Strandberg¹⁴⁸, S. Strandberg^{147a,147b}, A. Strandlie¹¹⁸, E. Strauss¹⁴⁴, M. Strauss¹¹², P. Strizenec^{145b}, R. Ströhmer¹⁷⁵, D.M. Strom¹¹⁵, R. Stroynowski⁴⁰, A. Struebig¹⁰⁵, S.A. Stucci¹⁷, B. Stugu¹⁴, N.A. Styles⁴², D. Su¹⁴⁴, J. Su¹²⁴, R. Subramaniam⁷⁸, A. Succurro¹², Y. Sugaya¹¹⁷, C. Suhr¹⁰⁷, M. Suk¹²⁷, V.V. Sulin⁹⁵, S. Sultansoy^{4c}, T. Sumida⁶⁷, S. Sun⁵⁷, X. Sun^{33a}, J.E. Sundermann⁴⁸, K. Suruliz¹⁴⁰, G. Susinno^{37a,37b}, M.R. Sutton¹⁵⁰, Y. Suzuki⁶⁵, M. Svatos¹²⁶, S. Swedish¹⁶⁹, M. Swiatkowski¹⁴⁴, I. Sykora^{145a}, T. Sykora¹²⁸, D. Ta⁸⁹, C. Taccini^{135a,135b}, K. Tackmann⁴², J. Taenzer¹⁵⁹, A. Taffard¹⁶⁴, R. Tahirout^{160a}, N. Taiblum¹⁵⁴, H. Takai²⁵, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴¹, Y. Takubo⁶⁵, M. Talby⁸⁴, A.A. Talyshev^{108,t}, J.Y.C. Tam¹⁷⁵, K.G. Tan⁸⁷, J. Tanaka¹⁵⁶, R. Tanaka¹¹⁶, S. Tanaka¹³², S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴³, B.B. Tannenwald¹¹⁰, N. Tannoury²¹, S. Tapprogge⁸², S. Tarem¹⁵³, F. Tarrade²⁹, G.F. Tartarelli^{90a}, P. Tas¹²⁸, M. Tasevsky¹²⁶, T. Tashiro⁶⁷, E. Tassi^{37a,37b}, A. Tavares Delgado^{125a,125b}, Y. Tayalati^{136d}, F.E. Taylor⁹³, G.N. Taylor⁸⁷, W. Taylor^{160b}, F.A. Teischinger³⁰, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate³⁰, P.K. Teng¹⁵², J.J. Teoh¹¹⁷, S. Terada⁶⁵, K. Terashi¹⁵⁶, J. Terron⁸¹, S. Terzo¹⁰⁰, M. Testa⁴⁷, R.J. Teuscher^{159,i}, J. Therhaag²¹, T. Theveneaux-Pelzer³⁴, J.P. Thomas¹⁸, J. Thomas-Wilsker⁷⁶, E.N. Thompson³⁵, P.D. Thompson¹⁸, P.D. Thompson¹⁵⁹, A.S. Thompson⁵³, L.A. Thomsen³⁶, E. Thomson¹²¹, M. Thomson²⁸, W.M. Thong⁸⁷, R.P. Thun^{88,*}, F. Tian³⁵, M.J. Tibbetts¹⁵, V.O. Tikhomirov^{95,ag}, Yu.A. Tikhonov^{108,t}, S. Timoshenko⁹⁷, E. Tiouchichine⁸⁴, P. Tipton¹⁷⁷, S. Tisserant⁸⁴, T. Todorov⁵, S. Todorova-Nova¹²⁸,

B. Toggerson⁷, J. Tojo⁶⁹, S. Tokár^{145a}, K. Tokushuku⁶⁵, K. Tollefson⁸⁹, L. Tomlinson⁸³, M. Tomoto¹⁰², L. Tompkins³¹, K. Toms¹⁰⁴, N.D. Topilin⁶⁴, E. Torrence¹¹⁵, H. Torres¹⁴³, E. Torró Pastor¹⁶⁸, J. Toth^{84,ah}, F. Touchard⁸⁴, D.R. Tovey¹⁴⁰, H.L. Tran¹¹⁶, T. Trefzger¹⁷⁵, L. Tremblet³⁰, A. Tricoli³⁰, I.M. Trigger^{160a}, S. Trincaz-Duvoid⁷⁹, M.F. Tripiana¹², W. Trischuk¹⁵⁹, B. Trocmé⁵⁵, C. Troncon^{90a}, M. Trottier-McDonald¹⁴³, M. Trovatelli^{135a,135b}, P. True⁸⁹, M. Trzebinski³⁹, A. Trzupek³⁹, C. Tsarouchas³⁰, J.C.-L. Tseng¹¹⁹, P.V. Tsiarehsha⁹¹, D. Tsionou¹³⁷, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹², V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁶, V. Tsulaia¹⁵, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁹, A. Tudorache^{26a}, V. Tudorache^{26a}, A.N. Tuna¹²¹, S.A. Tupputi^{20a,20b}, S. Turchikhin^{98,af}, D. Turecek¹²⁷, I. Turk Cakir^{4d}, R. Turra^{90a,90b}, P.M. Tuts³⁵, A. Tykhonov⁴⁹, M. Tylmad^{147a,147b}, M. Tyndel¹³⁰, K. Uchida²¹, I. Ueda¹⁵⁶, R. Ueno²⁹, M. Ughetto⁸⁴, M. Ugland¹⁴, M. Uhlenbrock²¹, F. Ukegawa¹⁶¹, G. Unal³⁰, A. Undrus²⁵, G. Unel¹⁶⁴, F.C. Ungaro⁴⁸, Y. Unno⁶⁵, C. Unverdorben⁹⁹, D. Urbaniec³⁵, P. Urquijo⁸⁷, G. Usai⁸, A. Usanova⁶¹, L. Vacavant⁸⁴, V. Vacek¹²⁷, B. Vachon⁸⁶, N. Valencic¹⁰⁶, S. Valentinetti^{20a,20b}, A. Valero¹⁶⁸, L. Valery³⁴, S. Valkar¹²⁸, E. Valladolid Gallego¹⁶⁸, S. Vallecorsa⁴⁹, J.A. Valls Ferrer¹⁶⁸, W. Van Den Wollenberg¹⁰⁶, P.C. Van Der Deijl¹⁰⁶, R. van der Geer¹⁰⁶, H. van der Graaf¹⁰⁶, R. Van Der Leeuw¹⁰⁶, D. van der Ster³⁰, N. van Eldik³⁰, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴³, I. van Vulpen¹⁰⁶, M.C. van Woerden³⁰, M. Vanadia^{133a,133b}, W. Vandelli³⁰, R. Vanguri¹²¹, A. Vaniachine⁶, P. Vankov⁴², F. Vannucci⁷⁹, G. Vardanyan¹⁷⁸, R. Vari^{133a}, E.W. Varnes⁷, T. Varol⁸⁵, D. Varouchas⁷⁹, A. Vartapetian⁸, K.E. Varvell¹⁵¹, F. Vazeille³⁴, T. Vazquez Schroeder⁵⁴, J. Veatch⁷, F. Veloso^{125a,125c}, S. Veneziano^{133a}, A. Ventura^{72a,72b}, D. Ventura⁸⁵, M. Venturi¹⁷⁰, N. Venturi¹⁵⁹, A. Venturini²³, V. Vercesi^{120a}, M. Verducci^{133a,133b}, W. Verkerke¹⁰⁶, J.C. Vermeulen¹⁰⁶, A. Vest⁴⁴, M.C. Vetterli^{143,d}, O. Viazlo⁸⁰, I. Vichou¹⁶⁶, T. Vickey^{146c,ai}, O.E. Vickey Boeriu^{146c}, G.H.A. Viehhauser¹¹⁹, S. Viel¹⁶⁹, R. Vigne³⁰, M. Villa^{20a,20b}, M. Villaplana Perez^{90a,90b}, E. Vilucchi⁴⁷, M.G. Vincter²⁹, V.B. Vinogradov⁶⁴, J. Virzi¹⁵, I. Vivarelli¹⁵⁰, F. Vives Vaque³, S. Vlachos¹⁰, D. Vladoiu⁹⁹, M. Vlasak¹²⁷, A. Vogel²¹, M. Vogel^{32a}, P. Vokac¹²⁷, G. Volpi^{123a,123b}, M. Volpi⁸⁷, H. von der Schmitt¹⁰⁰, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁸, K. Vorobev⁹⁷, M. Vos¹⁶⁸, R. Voss³⁰, J.H. Vossebeld⁷³, N. Vranjes¹³⁷, M. Vranjes Milosavljevic^{13a}, V. Vrba¹²⁶, M. Vreeswijk¹⁰⁶, T. Vu Anh⁴⁸, R. Vuillermet³⁰, I. Vukotic³¹, Z. Vykydal¹²⁷, P. Wagner²¹, W. Wagner¹⁷⁶, H. Wahlberg⁷⁰, S. Wahrmund⁴⁴, J. Wakabayashi¹⁰², J. Walder⁷¹, R. Walker⁹⁹, W. Walkowiak¹⁴², R. Wall¹⁷⁷, P. Waller⁷³, B. Walsh¹⁷⁷, C. Wang^{152,aj}, C. Wang⁴⁵, F. Wang¹⁷⁴, H. Wang¹⁵, H. Wang⁴⁰, J. Wang⁴², J. Wang^{33a}, K. Wang⁸⁶, R. Wang¹⁰⁴, S.M. Wang¹⁵², T. Wang²¹, X. Wang¹⁷⁷, C. Wanotayaroj¹¹⁵, A. Warburton⁸⁶, C.P. Ward²⁸, D.R. Wardrope⁷⁷, M. Warsinsky⁴⁸, A. Washbrook⁴⁶, C. Wasicki⁴², P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵¹, M.F. Watson¹⁸, G. Watts¹³⁹, S. Watts⁸³, B.M. Waugh⁷⁷, S. Webb⁸³, M.S. Weber¹⁷, S.W. Weber¹⁷⁵, J.S. Webster³¹, A.R. Weidberg¹¹⁹, P. Weigell¹⁰⁰, B. Weinert⁶⁰, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Weits¹⁰⁶, P.S. Wells³⁰, T. Wenaus²⁵, D. Wendland¹⁶, Z. Weng^{152,ae}, T. Wengler³⁰, S. Wenig³⁰, N. Wormes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Wessels^{58a}, J. Wetter¹⁶², K. Whalen²⁹, A. White⁸, M.J. White¹, R. White^{32b}, S. White^{123a,123b}, D. Whiteson¹⁶⁴, D. Wicke¹⁷⁶, F.J. Wickens¹³⁰, W. Wiedenmann¹⁷⁴, M. Wielers¹³⁰, P. Wienemann²¹, C. Wigglesworth³⁶, L.A.M. Wiik-Fuchs²¹, P.A. Wijeratne⁷⁷, A. Wildauer¹⁰⁰, M.A. Wildt^{42,ak}, H.G. Wilkens³⁰, J.Z. Will⁹⁹, H.H. Williams¹²¹, S. Williams²⁸, C. Willis⁸⁹, S. Willocq⁸⁵, A. Wilson⁸⁸, J.A. Wilson¹⁸, I. Wingerter-Seetz⁵, F. Winklmeier¹¹⁵, B.T. Winter²¹, M. Wittgen¹⁴⁴, T. Wittig⁴³, J. Wittkowski⁹⁹, S.J. Wollstadt⁸², M.W. Wolter³⁹, H. Wolters^{125a,125c}, B.K. Wosiek³⁹, J. Wotschack³⁰, M.J. Woudstra⁸³, K.W. Wozniak³⁹, M. Wright⁵³, M. Wu⁵⁵, S.L. Wu¹⁷⁴, X. Wu⁴⁹, Y. Wu⁸⁸, E. Wulf³⁵, T.R. Wyatt⁸³, B.M. Wynne⁴⁶, S. Xella³⁶, M. Xiao¹³⁷, D. Xu^{33a}, L. Xu^{33b,al}, B. Yabsley¹⁵¹, S. Yacoub^{146b,am}, R. Yakabe⁶⁶, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁶, Y. Yamaguchi¹¹⁷, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁶, T. Yamamura¹⁵⁶, T. Yamanaka¹⁵⁶, K. Yamauchi¹⁰², Y. Yamazaki⁶⁶, Z. Yan²², H. Yang^{33e}, H. Yang¹⁷⁴, U.K. Yang⁸³, Y. Yang¹¹⁰, S. Yanush⁹², L. Yao^{33a}, W.-M. Yao¹⁵, Y. Yasu⁶⁵, E. Yatsenko⁴², K.H. Yau Wong²¹, J. Ye⁴⁰, S. Ye²⁵, A.L. Yen⁵⁷, E. Yildirim⁴², M. Yilmaz^{4b}, R. Yoosoofmiya¹²⁴, K. Yorita¹⁷², R. Yoshida⁶, K. Yoshihara¹⁵⁶, C. Young¹⁴⁴, C.J.S. Young³⁰, S. Youssef²², D.R. Yu¹⁵, J. Yu⁸, J.M. Yu⁸⁸, J. Yu¹¹³, L. Yuan⁶⁶, A. Yurkewicz¹⁰⁷, I. Yusuff^{28,an}, B. Zabinski³⁹, R. Zaidan⁶², A.M. Zaitsev^{129,aa}, A. Zaman¹⁴⁹, S. Zambito²³, L. Zanello^{133a,133b}, D. Zanzi¹⁰⁰, C. Zeitnitz¹⁷⁶, M. Zeman¹²⁷, A. Zemla^{38a}, K. Zengel²³, O. Zenin¹²⁹, T. Ženiš^{145a}, D. Zerwas¹¹⁶, G. Zevi della Porta⁵⁷, D. Zhang⁸⁸, F. Zhang¹⁷⁴, H. Zhang⁸⁹,

J. Zhang⁶, L. Zhang¹⁵², X. Zhang^{33d}, Z. Zhang¹¹⁶, Z. Zhao^{33b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁹, B. Zhou⁸⁸, L. Zhou³⁵, N. Zhou¹⁶⁴, C.G. Zhu^{33d}, H. Zhu^{33a}, J. Zhu⁸⁸, Y. Zhu^{33b}, X. Zhuang^{33a}, K. Zhukov⁹⁵, A. Zibell¹⁷⁵, D. Zieminska⁶⁰, N.I. Zimine⁶⁴, C. Zimmermann⁸², R. Zimmermann²¹, S. Zimmermann²¹, S. Zimmermann⁴⁸, Z. Zinonos⁵⁴, M. Ziolkowski¹⁴², G. Zobernig¹⁷⁴, A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, G. Zurzolo^{103a,103b}, V. Zutshi¹⁰⁷, L. Zwalinski³⁰

¹ Department of Physics, University of Adelaide, Adelaide, Australia

² Physics Department, SUNY Albany, Albany, NY, United States

³ Department of Physics, University of Alberta, Edmonton, AB, Canada

⁴ (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Division of Physics, TOBB University of Economics and Technology, Ankara;

(d) Turkish Atomic Energy Authority, Ankara, Turkey

⁵ LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States

⁷ Department of Physics, University of Arizona, Tucson, AZ, United States

⁸ Department of Physics, The University of Texas at Arlington, Arlington, TX, United States

⁹ Physics Department, University of Athens, Athens, Greece

¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece

¹¹ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹² Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

¹³ (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States

¹⁶ Department of Physics, Humboldt University, Berlin, Germany

¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

¹⁹ (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

²⁰ (a) INFN Sezione di Bologna, Italy; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

²¹ Physikalisches Institut, University of Bonn, Bonn, Germany

²² Department of Physics, Boston University, Boston, MA, United States

²³ Department of Physics, Brandeis University, Waltham, MA, United States

²⁴ (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ),

Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

²⁵ Physics Department, Brookhaven National Laboratory, Upton, NY, United States

²⁶ (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania

²⁷ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

²⁸ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

²⁹ Department of Physics, Carleton University, Ottawa, ON, Canada

³⁰ CERN, Geneva, Switzerland

³¹ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States

³² (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

³³ (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui;

(c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Physics Department, Shanghai Jiao Tong University, Shanghai, China

³⁴ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

³⁵ Nevis Laboratory, Columbia University, Irvington, NY, United States

³⁶ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

³⁷ (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy

³⁸ (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

³⁹ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

⁴⁰ Physics Department, Southern Methodist University, Dallas, TX, United States

⁴¹ Physics Department, University of Texas at Dallas, Richardson, TX, United States

⁴² DESY, Hamburg and Zeuthen, Germany

⁴³ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

⁴⁴ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

⁴⁵ Department of Physics, Duke University, Durham, NC, United States

⁴⁶ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy

⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

⁴⁹ Section de Physique, Université de Genève, Geneva, Switzerland

⁵⁰ (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy

⁵¹ (a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi, Georgia; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

⁵² II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

⁵³ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

⁵⁴ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

⁵⁶ Department of Physics, Hampton University, Hampton, VA, United States

⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States

⁵⁸ (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg;

(c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

⁵⁹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

⁶⁰ Department of Physics, Indiana University, Bloomington, IN, United States

⁶¹ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

⁶² University of Iowa, Iowa City, IA, United States

⁶³ Department of Physics and Astronomy, Iowa State University, Ames, IA, United States

⁶⁴ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

- ⁶⁵ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁶ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁷ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁸ Kyoto University of Education, Kyoto, Japan
- ⁶⁹ Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁰ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷¹ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷² ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷³ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁴ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁵ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁶ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁷ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁸ Louisiana Tech University, Ruston, LA, United States
- ⁷⁹ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸⁰ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸¹ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸² Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸³ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁴ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁵ Department of Physics, University of Massachusetts, Amherst, MA, United States
- ⁸⁶ Department of Physics, McGill University, Montreal, QC, Canada
- ⁸⁷ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁸ Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- ⁸⁹ Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- ⁹⁰ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹¹ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- ⁹² National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- ⁹³ Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
- ⁹⁴ Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- ⁹⁵ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁶ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁷ Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁸ D.V.Skobeltzyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ⁹⁹ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰⁰ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰¹ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰² Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰³ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁴ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- ¹⁰⁵ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁶ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁷ Department of Physics, Northern Illinois University, DeKalb, IL, United States
- ¹⁰⁸ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁹ Department of Physics, New York University, New York, NY, United States
- ¹¹⁰ Ohio State University, Columbus, OH, United States
- ¹¹¹ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹² Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- ¹¹³ Department of Physics, Oklahoma State University, Stillwater, OK, United States
- ¹¹⁴ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁵ Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- ¹¹⁶ LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ¹¹⁷ Graduate School of Science, Osaka University, Osaka, Japan
- ¹¹⁸ Department of Physics, University of Oslo, Oslo, Norway
- ¹¹⁹ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²⁰ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²¹ Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
- ¹²² Petersburg Nuclear Physics Institute, Gatchina, Russia
- ¹²³ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²⁴ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
- ¹²⁵ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC de Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ¹²⁶ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁷ Czech Technical University in Prague, Praha, Czech Republic
- ¹²⁸ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- ¹²⁹ State Research Center Institute for High Energy Physics, Protvino, Russia
- ¹³⁰ Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³¹ Physics Department, University of Regina, Regina, SK, Canada
- ¹³² Ritsumeikan University, Kusatsu, Shiga, Japan
- ¹³³ ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ¹³⁴ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ¹³⁵ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- ¹³⁶ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; ^(b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;
- ¹³⁷ Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- ¹³⁸ DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- ¹³⁹ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
- ¹⁴⁰ Department of Physics, University of Washington, Seattle, WA, United States

- ¹⁴⁰ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
¹⁴¹ Department of Physics, Shinshu University, Nagano, Japan
¹⁴² Fachbereich Physik, Universität Siegen, Siegen, Germany
¹⁴³ Department of Physics, Simon Fraser University, Burnaby, BC, Canada
¹⁴⁴ SLAC National Accelerator Laboratory, Stanford, CA, United States
¹⁴⁵ ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
¹⁴⁶ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
¹⁴⁷ ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
¹⁴⁸ Physics Department, Royal Institute of Technology, Stockholm, Sweden
¹⁴⁹ Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
¹⁵⁰ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
¹⁵¹ School of Physics, University of Sydney, Sydney, Australia
¹⁵² Institute of Physics, Academia Sinica, Taipei, Taiwan
¹⁵³ Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
¹⁵⁴ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
¹⁵⁵ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
¹⁵⁶ International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
¹⁵⁷ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
¹⁵⁸ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
¹⁵⁹ Department of Physics, University of Toronto, Toronto, ON, Canada
¹⁶⁰ ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
¹⁶¹ Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
¹⁶² Department of Physics and Astronomy, Tufts University, Medford, MA, United States
¹⁶³ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
¹⁶⁴ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
¹⁶⁵ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
¹⁶⁶ Department of Physics, University of Illinois, Urbana, IL, United States
¹⁶⁷ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
¹⁶⁸ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
¹⁶⁹ Department of Physics, University of British Columbia, Vancouver, BC, Canada
¹⁷⁰ Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
¹⁷¹ Department of Physics, University of Warwick, Coventry, United Kingdom
¹⁷² Waseda University, Tokyo, Japan
¹⁷³ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
¹⁷⁴ Department of Physics, University of Wisconsin, Madison, WI, United States
¹⁷⁵ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
¹⁷⁶ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
¹⁷⁷ Department of Physics, Yale University, New Haven, CT, United States
¹⁷⁸ Yerevan Physics Institute, Yerevan, Armenia
¹⁷⁹ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

^a Also at Department of Physics, King's College London, London, United Kingdom.

^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

^d Also at TRIUMF, Vancouver BC, Canada.

^e Also at Department of Physics, California State University, Fresno, CA, United States.

^f Also at Tomsk State University, Tomsk, Russia.

^g Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

^h Also at Università di Napoli Parthenope, Napoli, Italy.

ⁱ Also at Institute of Particle Physics (IPP), Canada.

^j Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

^k Also at Chinese University of Hong Kong, China.

^l Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

^m Also at Louisiana Tech University, Ruston, LA, United States.

ⁿ Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

^o Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.

^p Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

^q Also at CERN, Geneva, Switzerland.

^r Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

^s Also at Manhattan College, New York, NY, United States.

^t Also at Novosibirsk State University, Novosibirsk, Russia.

^u Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

^v Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.

^w Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

^x Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

^y Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.

^z Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.

^{aa} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

^{ab} Also at Section de Physique, Université de Genève, Geneva, Switzerland.

^{ac} Also at International School for Advanced Studies (SISSA), Trieste, Italy.

^{ad} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.

^{ae} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

^{af} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

^{ag} Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.

^{ah} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

^{ai} Also at Department of Physics, Oxford University, Oxford, United Kingdom.

^{aj} Also at Department of Physics, Nanjing University, Jiangsu, China.

^{ak} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

^{al} Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States.

^{am} Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.

^{an} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

* Deceased.